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Vacuum Jacketed Composite Propulsion Feedlines for Cryogenic Launch and Space Vehicles

by

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MARTIN MARIETTA CORPORATION

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16. Abstract

Thin metallic liners that provide leak-free service in cryogenic propulsion systems are overwrapped with a glass-fiber composite that provides strength and protection from handling damage. The resultant tube is lightweight, strong, and has a low thermal flux. The inside commodity flow line and the outside vacuum jacket were fabricated using this method. Several types of vacuum jackets were fabricated and tested at operating temperatures from 294 to 21 K (+70 to -423°F) and operating pressures up to 69 N/cm^2 (100 psi). The primary objective of the program was to develop vacuum jacket concepts, using previously developed concepts for the inner line. All major program objectives were met resulting in a design concept that is adaptable to a wide range of aerospace vehicle requirements. Major items of development included convolution of thin metallic sections up to 46 cm (18 in.) in diameter, design and fabrication of an extremely lightweight tension membrane concept for the vacuum jacket, and analytical tools that predict the failure mode and levels. An attempt to bond the vacuum jacket liner to the composite overwrap was unsuccessful resulting in the premature failure of several lines. A redesign, which is not dependent upon bonding, was successful. Weight savings of over 50% are attainable for vacuum jacketed composite feedlines when compared to conventional configurations and materials of construction.

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FOREWORD

The work described herein was conducted by Martin Marietta Corporation, Denver Division, under NASA Contract NAS3-16762, under the management of the NASA Project Manager, Mr. Joseph Notardonato, Propulsion Systems Branch, NASA-Lewis Research Center, Cleveland, Ohio.

This final report is published in two volumes: Volume I describes the results of the program and Volume II contains related appendixes.

In addition to the stated authors, the following persons provided major assistance: Messrs. Clifford S. Foster, John R. Lager, Gary E. Wilson, Stanley R. Tomer, Walter L. McKenna, William E. Mohr, Timothy P. Quinn, Connie E. Lynch, and Donald A. Stang. Major contributors at the Grumman Aerospace Corporation included Messrs. Michael J. Martin, Benjamin Aleck, and Carlos Cacho-Negrete.

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SYMBOLS

A	Area, cm^2 ($in.^2$)
A_L	Cross-sectional liner area, cm^2 ($in.^2$)
A_o	Cross-sectional overwrap area, cm^2 ($in.^2$)
a	Membrane width, cm (in.)
b	Membrane length, cm (in.)
b	Base, cm (in.)
C	Circumference, cm (in.)
C_p	Specific heat, cal/g/°K (Btu/lb/°F)
D	Diameter, cm (in.)
d	Resonant frequency, Hz
dB	Decibel
ε	Emittance
E_c	Composite modulus of elasticity (metal liner plus overwrap), N/cm^2 (psi)
E_L	Modulus of elasticity (liner), N/cm^2 (psi)
E_o	Modulus of elasticity (overwrap), N/cm^2 (psi)
E_θ	Circumferential modulus of elasticity, N/cm^2 (psi)
E_ϕ	Meridional modulus of elasticity, N/cm^2 (psi)
e	Strain, cm/cm (in./in.)
e_L	Strain in liner, cm/cm (in./in.)
e_o	Strain in overwrap, cm/cm (in./in.)
e_x	Strain in x direction (along tube centerline), cm/cm (in./in.)
e_h	Strain in hoop direction, cm/cm (in./in.)
F	Force, N (lb)
F_L	Force in liner, N (lb)

F_o	Force in overwrap, N (lb)
F_S	Factor of safety
f_{mn}	Frequency for mode shape, Hz
G	Acceleration (number of g's)
g	Acceleration of gravity, cm/sec^2 (in./sec^2)
g_o	Acceleration spectral density, g^2/Hz
Hz	Frequency in Hertz
h	Height, cm (in.)
I	Moment of inertia, cm^4 (in.^{4})
i	Current, amperes
L	Length, cm (in.)
γ	Hottel gray body factor
M	Molecular weight, moles
m	Bending moment, cm-N (in.-lb)
mn	Mode shape
n	Number of cycles
P	Pressure, N/cm^2 (psi)
P_N	Load per unit length, N/cm (lb/in.)
P_L	Load in liner, N/cm (lb/in.)
P_o	Load in overwrap N/cm (lb/in.)
P_u	Uniform load intensity
ΔP	Pressure drop N/cm^2 (psi or microns)
Q	Flow rate
Q_F	Magnification factor
q	Radiation heat transfer, W/m (Btu/hr-ft)
R	Ring radius, cm (in.)

R	Ideal gas constant, J °K^{-1} mol^{-1} (lb-mole °F)
R	Resistances, ohms
r_1	Radius of curvature, cm (in.)
r	Radius, cm (in.)
s	Time, seconds
S	Stress, N/cm^2 ($lb/in.^2$)
S_h	Stress in hoop direction, N/cm^2 ($lb/in.^2$)
S_L	Stress in liner, N/cm^2 ($lb/in.^2$)
S_o	Stress in overwrap, N/cm^2 ($lb/in.^2$)
S_x	Stress in x direction, N/cm^2 ($lb/in.^2$)
S_y	Yield stress, N/cm^2 ($lb/in.^2$)
S_z	Stress in z direction, N/cm^2 ($lb/in.^2$)
S_ϕ	Meridional stress, N/cm^2 ($lb/in.^2$)
T	Temperature, °K (°F)
T	Torque, cm-N (in.-lb)
t	Thickness, cm (in.)
ΔT_L	Change in liner temperature, °K (°R)
ΔT_o	Change in overwrap temperature, °K (°R)
V	Volume, liters ($in.^3$)
W	Weight, kg (lb)
w	Weight/unit area, kg/cm^2 ($lb/in.^2$)
X	Deflection ratio
Y	Distance from neutral axis to extreme fiber, cm (in.)
Z	Stefan-Boltzmann constant, W/m^2-K^4 (Btu/ft^2-hr °R^4)
Z_L	Uniform tension per unit length, N/cm (lb/in.)
σ	Sigma (statistical)

δ	Damping ratio
ϕ	Fluctuating pressure spectral density, $\frac{(N/cm^2)^2}{Hz} \left(\frac{psi^2}{Hz}\right)$
μ	Microns of Hg
Δ	Deflection, cm (in.)
α	Coefficient of thermal expansion, cm/cm/°K (in./in./°F)
α_L	Liner coefficient of thermal expansion in axial direction, cm/cm/°K (in./in./°F)
α_o	Overwrap coefficient of thermal expansion in axial direction, cm/cm/°K (in./in./°F)
ν	Poisson's ratio
ρ	Density, kg/cm^3 ($lb/in.^3$)

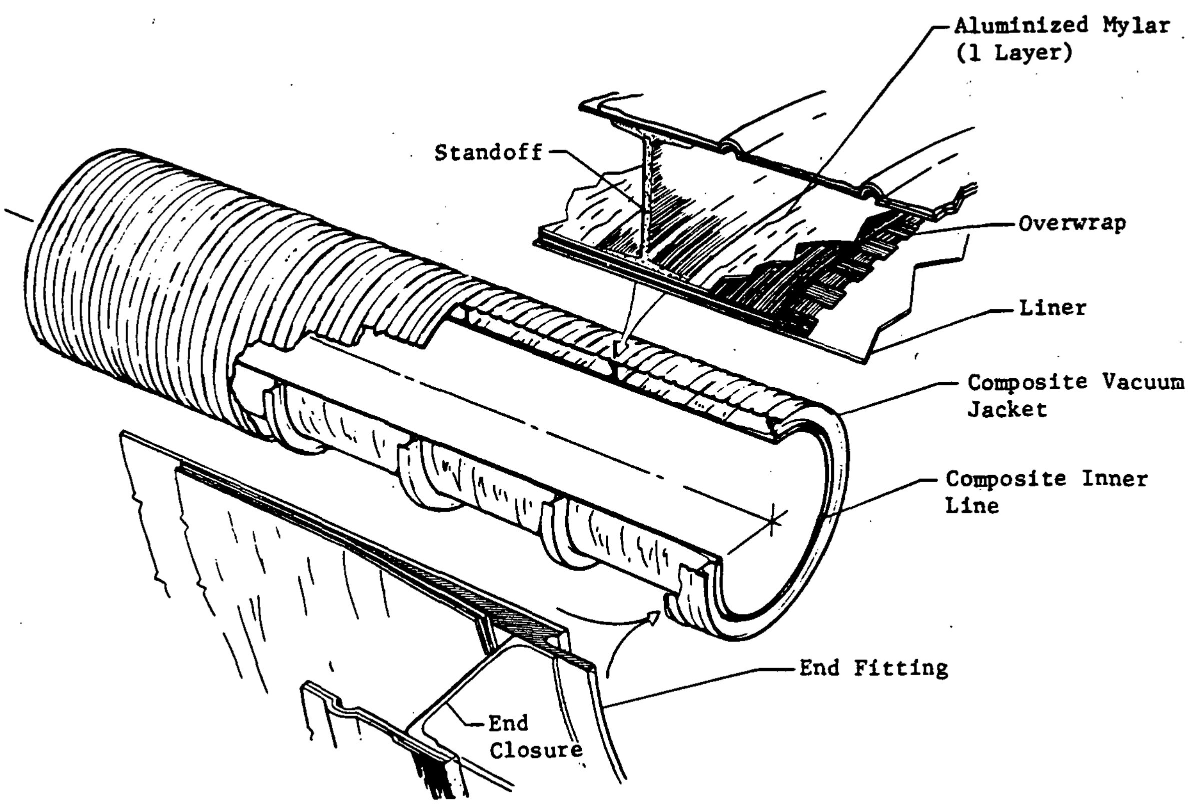
Subscripts

AT	Axial tension
B	Bending
BL	Bending in liner
c	Composite
c	Curved section
DTC	Differential thermal contraction
IP	Internal pressure
i	Outside surface of inner line
L	Liner
o	Overwrap, or the inside surface of the vacuum jacket
rms	Random
st	Shear stress due to torsion
s	Straight section
T	Total
TC	Tensile stress in inner line liner
x	Longitudinal Direction

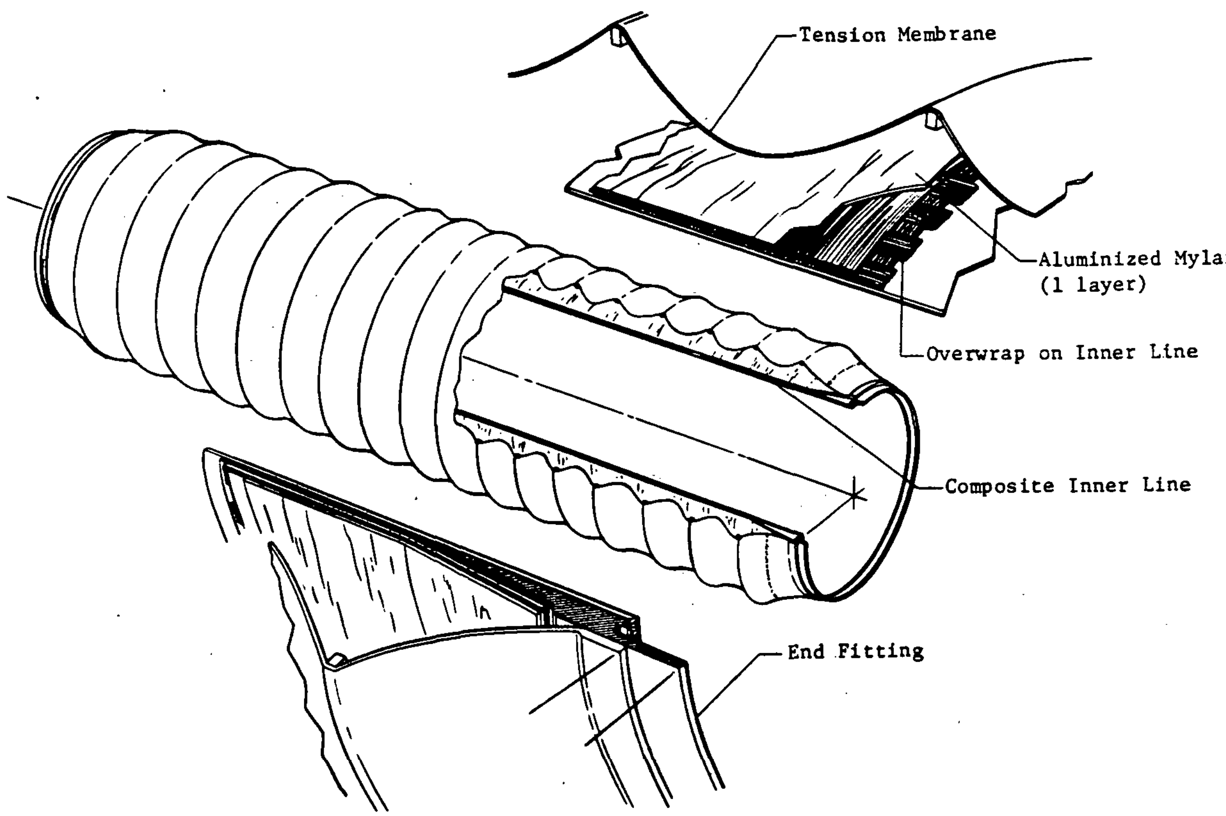
DEFINITION OF TERMS

A listing of commonly used terms and their definitions follows. Familiarity with these terms should help the reader to understand the technical aspects of this document.

Inner Line	Line carrying the commodity.
Vacuum Jacket	Outer line.
Composite Vacuum Jacket	A vacuum jacket concept that incorporates a thin metallic liner and composite material to provide strength and handling damage resistance. A typical composite vacuum jacket is shown in the sketch.



Tension Membrane Vacuum Jacket	A vacuum jacket concept that relies on tension in the metallic structure for load carrying. This concept has the appearance of a suspension bridge and, because the structure is in tension it can be loaded heavily without loss of reliability. It is a very lightweight concept. A tension membrane vacuum jacket is shown in the sketch.



Overwrap	Total fiberglass composite thickness 0.05 cm (0.020 in.) consisting of 2 layers of hoop wrap and a ½ layer of axial cloth or 2 layers of hoop wrap applied in a criss-cross pattern.
Liner	Thin wall metal tube under the overwrap.

Standoff	Support between the vacuum jacket and the inner line.
End Closure	Metal membrane that seals the vacuum annulus between the inner line and the vacuum jacket.
Stiff End Closure	End closure capable of transferring all the loading due to thermal contraction of the inner line to the vacuum jacket and the load caused by external pressure to the inner line.
Flexible End Closure	End closure incapable of transferring the loading caused by thermal contraction of the inner line to the vacuum jacket; divides the load caused by external pressure between the inner line and the vacuum jacket.
End Fitting	Metal ring welded to the ends of the liner providing a surface for welding the end closure and a butt weld end for attaching one tube to another.
Solid State Bonding	Explosive bonding technique used to join two dissimilar metals such as aluminum to Inconel or stainless steel.

SUMMARY

This is the final report of a 14-month program that was conducted under Contract NAS3-16762. The objective of the program was to develop lightweight vacuum jacketed composite tubing for use as cryogenic plumbing on launch and space vehicles. Twelve tubes of two different inside diameters [13 and 38 cm (5 and 15 in.)] were fabricated in 3 different types of each size. Each tube was 61 cm (24 in.) long. The tubes were joined together in sets of two for testing.

The tubing in this program was intended to be representative of flight configuration for cryogenic feedlines for LH_2 service where vacuum jackets are mandatory. The sizes are representative of the Shuttle main propulsion and the Space Tug feedlines.

An analysis program assessed thermal, structural, weight, and fabrication parameters, and formed the basis for the tubing design. Ultimately, thin metallic liners 0.008 to 0.013 cm (0.003 to 0.005 in.) thick were selected as the primary load-carrying member. Ten of these liners were overwrapped with glass-fibers impregnated with a resin matrix suitable for cryogenic service for the inner line. A resin matrix suitable for ambient and slightly elevated temperatures was used for the outer jacket. The overwrapped composite was used to strengthen the liners and protect them from handling damage. Two of the tubes were of the tension membrane type consisting of a composite overwrapped inner line and a nonoverwrapped vacuum jacket. Concurrent with the analysis effort, preliminary tests were performed to aid in selecting materials and methods of construction.

The 12 tubes required for test were designed, fabricated, and verified ready for test. Tube fabrication included liner welding, joining of the liners to end fittings, instrumentation installation, overwrapping and curing, and a series of in-process leak checks and other quality determinations. After these individual subassembly steps were completed, the inner line and the vacuum jacket were joined by welding. Vacuum outgassing and vacuum acquisition completed the fabrication.

The tubes were subjected to a series of tests including leakage, pressure cycling, temperature cycling, pressure surge, acoustics, and burst. One of the tubes failed during the first vacuum acquisition test. It was subsequently determined that the bond between the jacket liner and overwrap failed because of atmospheric pressure acting between the overwrap and the liner.

A temporary fix, installed to permit testing to continue, proved capable of protecting the tubes and transferring the loading to the overwrap from the liner, but it was rather complex and had a low reliability. During subsequent testing several other lines became separated from the overwrap and immediately failed.

A single tube of a modified vacuum jacket design using a metal liner 0.030 cm (0.012 in.) thick was fabricated. This liner was capable of carrying external pressure but was still susceptible to handling damage. The vacuum jacket was overwrapped, in the same manner as the other test specimens, to provide protection from damage during handling. This tube passed all tests, was damage-resistant and of lighter weight than conventional all-metal vacuum jacketed lines.

The tension membrane concept, designed and fabricated by Grumman Aerospace Corporation, passed all tests and becomes a very strong candidate for vacuum jacketed feedlines. Its two main advantages are the very lightweight construction and the metal is in the predictable tensile stress mode instead of being subjected to the less predictable compressive buckling mode. The tension membrane concept was tested and evaluated by Martin Marietta Corporation concurrently with the composite vacuum jacket concepts. Complete design and fabrication details of the tension membrane concept are included in Appendix E, *Vacuum Jacketed Composite Lines, Final Report*, by the Grumman Aerospace Corporation.

The results of this and earlier programs clearly verify the advantages of using glass-fiber composite tubing in cryogenic propellant service for vacuum jacketed feedlines. Some of the advantages include low thermal flux, lightweight construction, low-heat-soakback from engines, rapid chilldown, resistance to damage, and high strength. This can be accomplished with a moderate increase in cost--in many cases for less than \$60 per kg (\$25 per lb) of weight reduced.

Additional work is needed to more fully develop the bonding concept, and eliminate the leakage and outgassing problems in some designs. The leakage and outgassing problems can be solved through process control since several tubes have exhibited successful properties in both areas of concern. The bonding development will only be required if optimum weight savings are to be realized.

INTRODUCTION

In the continuing development of optimum performance cryogenic propulsion systems, there is considerable interest in improved thermal performance and in minimizing total system weight. Considering the high heat leak rates through conventional tubing systems, it is desirable that techniques be developed to produce feedlines using a low heat leak material such as composites, particularly if these feedlines also contribute to weight minimization.

In two recently completed programs, Contract NAS3-12047, *Glass-Fiber Tubing for Cryogenic Service* (ref. 1) and Contract NAS3-14370, *Composite Propulsion Feedlines for Cryogenic Space Vehicles* (ref. 2), Martin Marietta Corporation analyzed, designed, fabricated, and tested a series of composite propulsion feedlines designed to limit the heat transfer through this portion of the propulsion system. These feedlines incorporated a thin metal liner to provide a leakfree pressure carrier and compatibility with cryogenic propellants. These thin metal liners were overwrapped with a glass-fiber material using a suitable matrix. Because glass-fiber overwrap is a very good thermal insulator and the thin metal liner has a very small cross-sectional area, the thermal conductivity was reduced considerably in both radial and longitudinal directions. Program results confirm the desirability of this concept. Some of the advantages, in addition to low radial and axial thermal flux, are lightweight construction, low axial heat-soakback from engines or vaporizers, rapid childown, strength, and resistance to handling damage.

The 0.10 cm (0.040 in.) minimum wall thickness used for all-metal feedlines in a great majority of propulsion systems is dictated by handling and maintainability, not stresses. For example, an Inconel 718 or stainless steel tube with a 0.013 cm (0.005 in.) wall thickness could carry all internal pressure loads for many propulsion feedlines and tank vents but could not be handled without incurring damage. Composite tubing can be fabricated with the metal liner wall thickness of 0.013 cm (0.005 in.) and overwrapped with glass-fibers having low density and low thermal conductivity. The results are lighter feedlines with reduced thermal flux characteristics, low weight, and high resistance to damage.

The purpose of this program was to evaluate fiber composites for lightweight, vacuum jacketed, cryogenic line systems for space application. Both the inner line (commodity line) and the outer shell (vacuum jacket) were candidates for fiber composite technology.

Several problems had to be solved before lightweight low thermal flux tubing could be considered for use on a space vehicle such as Space Shuttle. Solution of these problems for the main

engine cryogenic plumbing was the intent of this program. The objective of the work was to design, fabricate, and evaluate glass-fiber composites for the inner lines and the vacuum jacket shell. Tubing specimens were designed, fabricated, and subjected to various portions of the specified test program. Specific items that were performed to accomplish the program objectives included:

1) selecting a set of boundaries for analysis and for use as design parameters;

2) modifying existing analytical models to incorporate analysis of glass-fiber overwrapped, metal-lined tubing, including the vacuum jackets;

3) using analytical models to assist in the design of the metal-lined tubing for optimum system weight and overall system performance;

4) designing test items using several vacuum jacket designs for performance comparison;

5) fabricating the 13 and 38 cm (5 and 15 in.) diameter feedline sections;

6) testing tubing to determine its capability to maintain a vacuum and to withstand necessary flight loads and requirements;

7) correlating experimental and analytical data to show the capability of the analytical model to predict tubing performance; and

8) reporting recommended modification or changes that would be incorporated in the design for flight-qualified feedlines.

The first task consisted of performing thermal, structural, weight, and fabrication analyses; and designing test items and test fixtures. Tube fabrication followed the design phase and included liner welding, joining of the liners to end fittings, instrumentation installation, overwrapping and curing, and a series of in-process leak checks. Much of the metal fabrication was subcontracted to thin metal bellows manufacturers. The test fixtures were fabricated concurrently with fabrication of the composite tubing test specimens consisting of:

1) 6 sections of 13 cm (5 in.) diameter inner lines with 20 cm (8 in.) diameter vacuum jackets, incorporating three different jacket design concepts; and

2) 6 sections of 38 cm (15 in.) diameter inner lines with 46 cm (18 in.) diameter vacuum jackets, also incorporating three different jacket design concepts.

Each section of tube was subjected to vacuum outgassing, strain cycling, pressure surge, acoustic, and external collapse testing.

A complete analysis of the fabrication and test data was performed to document the effectiveness, cost, reliability, and desirability of glass-fiber composite tubing for vacuum jacketed cryogenic space vehicle applications. Structural integrity and thermal quality were evaluated and compared to the predicted performance. Recommendations were made for design improvements based on the above comparison. The design criteria established in the initial design phase were updated as indicated by the data analysis.

All major program objectives were accomplished resulting in a usable concept for effectively improving thermal performance and reducing the weight of vacuum jacketed propulsion systems.

CONCEPTUAL DESIGN

Conceptual design activities consisted of establishing design criteria and characteristics of composite tubing that control design, performing analysis to evaluate these parameters, developing candidate configuration concepts, performing analysis of these concepts, and selecting five different designs for fabrication and test evaluation.

Design Criteria. - Table I depicts the vacuum jacketed composite line design criteria which were established based on contract and Space Shuttle requirements. These data were used for design and development of test requirements. The specific parts of a vacuum jacketed concept that were evaluated during this contract included:

1) inner line;

2) end closures;

3) standoffs, i.e., supports between inner line and vacuum jackets;

4) vacuum jacket liner material;

5) composite material;

6) vacuum ports;

7) vacuum acquisition and maintenance;

8) thermal expansion and contraction of the inner line versus the vacuum jacket;

9) vacuum carry-through or vapor seal;

10) bonding the overwrap to the metallic liner;

11) fabrication; and

12) overall structural and dynamic strength.

TABLE I. - DESIGN CRITERIA

Parameter	Requirement
1. Operating pressure	41 N/cm^2 (60 psia) for 5 to 25 cm (2 to 10 in.) I.D. tubes 69 N/cm^2 (100 psia) for 25 to 51 cm (10 to 20 in.) I.D. tubes
2. Proof pressure	62 N/cm^2 (90 psia) for 5 to 25 cm (2 to 10 in.) I.D. tubes 103 N/cm^2 (150 psia) for 25 to 51 cm (10 to 20 in.) I.D. tubes
3. Burst pressure	103 N/cm^2 (150 psia) for 5 to 25 cm (2 to 10 in.) I.D. tubes 172 N/cm^2 (250 psia) for 25 to 51 cm (10 to 20 in.) I.D. tubes
4. External collapse pressure	25 N/cm^2 (36.7 psid) for composite vacuum jackets 15 N/cm^2 (22 psid) for tension membrane vacuum jackets
5. Thermal cycles	200 cycles 20 K (-423°F) to ambient
6. Pressure cycles	200 cycles (ambient to operating pressure)
7. Pressure surges	10 cycles (ambient to operating pressure within 0.5 sec)
8. Acceleration	4g axial and lateral
9. Acoustics	160 db of random acoustic excitation for 450 seconds and 167 db for an additional 60 seconds
10. Design life	100 mission cycles for liftoff to handling and refurbishment as required between missions for a calendar life of 10 years
11. Radial thermal efficiency as a function of inner line to vacuum jacket emittance	$(\varepsilon) \leq 0.035$
12. Vacuum acquisition	$<1.3 \times 10^{-5}$ N/cm^2 (10^{-3} torr)
13. Vacuum maintenance	6.7×10^{-5} N/cm^2/day (5 μ/day) allowable pressure increase in the vacuum annulus
14. Inner line leak rate	$<10^{-8}$ scc/sec total, $<3 \times 10^{-10}$ scc/sec into the vacuum annulus

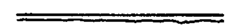
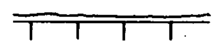
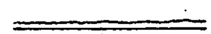
Concept Selection. - A vacuum jacketed composite line consists of a pressure carrying line (inner line), a vacuum jacket (outer line), end closures at each end of the vacuum jacket, standoffs, and vacuum acquisition ports. These items were evaluted to develop a conceptual configuration. The decision was made to use identical configuration inner lines, end closures, standoffs, and vacuum acquisition ports on all design concepts except the tension membrane. This approach resulted in the vacuum jacket becoming the major variable for evaluation.

Inner line: The inner line configuration was selected based on the development work on contracts NAS3-12047, *Low Thermal Flux Glass Fiber Tubing for Cryogenic Service* (ref. 1) and NAS3-14370, *Composite Propulsion Feedlines for Cryogenic Space Vehicles* (ref. 2). The selected configuration featured 0.008 cm (0.003 in.) thick and 0.013 cm (0.005 in.) thick Inconel 718 liners for 13 cm (5 in.) and 38 cm (15 in.) diameter liners, respectively, overwrapped with S/HTS glass-fibers in a 58-68R resin system. Butt weld type stainless steel end fittings are welded to the liners. The overwrap consists of a layer of machine hoop wrapped 20 end roving, a half layer of longitudinally oriented glass cloth, and a final layer of hoop wrap. Design analysis determined that the (1) inner line liner should be heat treated after joining it to the end fittings, (2) composite overwrap should be bonded to the liner to provide an axial compressive load capability of 17.8 kg/cm (100 lb/in.) required to resist the compressive load imposed by the tension membrane vacuum jacket, (3) composite should be covered with one layer of aluminized mylar to improve emissivity of the inner line, and (4) torsion and tension load carrying capability was more than adequate to survive predicted launch environments. These inner line design analyses are presented in Appendix A.

Vacuum jacket: Twelve vacuum jacket concepts were evaluated from which five concepts were selected for design, fabrication, and test with one concept chosen for both 13 cm (5 in.) and 38 cm (15 in.) inner line diameters.

These concepts and selection rationale are defined in Table II. The selected concepts are numbered from 1 to 5 and these numbers are referred to later in the report.

TABLE II. - VACUUM JACKET CONCEPTS AND SELECTION RATIONALE

Selected concept number	Selected concept inner line diameter, cm (in.)	Preliminary concept number		Description	Comments	Reasons for elimination
2	13, 38 (5, 15)	1		O.D. convolutes external glass	Simple fabrication	
4	13 (5)	2		I.D. convolutes external glass	Higher axial load harder to fabricate	
		3		I.D. or O.D. convolutes external glass integral bellows	No overwrap on bellows joint	Bellows and convolutes are redundant and not required. Low stiffness.
		4		Internal glass	Minimum gage liner	Exposed liner is susceptible to handling damage. Fabrication problems.
		5		Internal supports O.D. convolutes	More complex, lighter weight	Difficult to fabricate. O.D. convolutes should not be required with internal supports.
3	38 (15)	6		Internal supports no convolutes	Less complex, not lightweight.	
5	38 (15)	7a		Tension membrane jacket	Lightweight minimum gage liner. May require external protection for flight usage.	
		7b		With composite hoop bulkheads - composite over liner	Composite protects liner from damage.	Heavier weight concept than 7a.
		7c		With composite hoop bulkheads - composite under liner	Lightweight minimum gage liner	Difficult to fabricate. Heavier weight concept than 7a.
		8		I.D. convolutes, internal glass - O.D. foil	Lightweight and complex	Difficult to install internal stringers.
		9		O.D. and I.D. glass-foil or vapor deposited liner	Lightweight and complex	Further development required for vapor deposited liner.
		10		I.D. glass-vapor deposited liner	Lightweight and complex	Exposed liner is susceptible to handling damage. Further development required for vapor depositing.
1	13 (5)	11		O.D. glass node ribs	Simple fabrication	
		12		Honeycomb	Strong and complex	Diffcult to fabricate. Fabrication development is required.

Note: 1. One convolute to be provided for thermal contraction if required.
2. Bond metal liner to composites for all concepts except No. 7a.

Vacuum jacket liner material: Five materials whose characteristics are shown in Table III were considered for the vacuum jacket metallic liner. The criteria for material selection was modulus of elasticity, density, cost, and ease of fabrication. Stainless steel (304L) was selected as the material best satisfying these criteria. For the same weight lines, aluminum offers some additional buckling strength. This is because buckling strength is a function of material thickness. However, aluminum requires development of explosive bonding techniques to join the aluminum vacuum jacket to the Inconel 718 inner line. Titanium is not compatible for welding to stainless steel or Inconel and therefore was not selected. Types 304L and 21-6-9 stainless steel have the same modulus and density, type 304L, however, is the least expensive.

Vacuum jacket composite material: A preliminary stability analysis summary for the various overwrap fibers with Inconel, stainless steel, aluminum and titanium is presented in Table IV for a 20 cm (8 in,) diameter vacuum jacket. It is noted that boron permits a cylinder length between stiffeners of twice that of the other fibers, at about the same weight per unit length.* Thus, since the boron fibers require fewer hoop stiffeners, the boron will result in the least total line weight. The cylinder length and weight per unit length for the other fibers is about the same. The cost for the overwrap fibers, including impregnation with the resin system, follows.

S-Glass, \$29/kg (\$13/lb)

Graphite, \$550/kg (\$250/lb)

Boron, \$550/kg (\$250/lb)

PRD-49, \$110/kg (\$50/lb)

A comparison of overwrap weight and cost per unit length is provided in Figure 1.

Because of the substantial difference in cost, S-Glass was selected as the fiber system to be used for overwrapping the test specimens.

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*This analysis assumed a perfect bond between the overwrap and the vacuum jacket liner, which was not achieved on the test specimens. Without the bond, boron would provide very little weight advantage over the other composites.

TABLE III. - VACUUM JACKET LINER MATERIAL SELECTION

Material	Modulus of elasticity	Density	Cost, \$/kg (\$/lb)	Fabrication
*304L stainless steel	19.3×10^6 N/cm^2 (28×10^6 psi)	7.92 g/cm^3 (0.286 lb/in.^{3})	0.95 to 1.65 (0.43 to 0.75)	
21-6-9 stainless steel	19.7×10^6 N/cm^2 (28.5×10^6 psi)	7.92 g/cm^3 (0.286 lb/in.^{3})	2.2 (1.0)	
Inconel 718	20.0×10^6 N/cm^2 (29×10^6 psi)	8.20 g/cm^3 (0.296 lb/in.^{3})	37.4 (17.0)	More difficult to form than stainless steel.
Ti-6Aℓ-4V	11.4×10^6 N/cm^2 (16.5×10^5 psi)	4.43 g/cm^3 (0.16 lb/in.^{3})	20.7 (9.4)	Not compatible for welding to a stainless steel inner line. Requires explosive bonding a stainless steel end fitting for welding to inner line.
6061 aluminum	6.9×10^6 N/cm^2 (10×10^6 psi)	2.71 g/cm^3 (0.098 lb/in.^{3})	1.06 to 1.19 (0.48 to 0.54)	Same as above.

*Leak free welding was not achieved using 304L stainless steel 0.015 cm (0.006 in.) thick material for the vacuum jackets. The material was changed to 0.015 cm (0.006 in.) Inconnel 718 and the welds were performed without leakage.

TABLE IV. - PRELIMINARY STABILITY ANALYSIS SUMMARY
VACUUM JACKETS - ORTHOTROPIC CYLINDERS

Metal inner liner	Overwrap fibers	Cylinder length, ccm (in.)	Thickness inner liner, cm (in.)	Thickness overwrap, cm (in.)	Critical axial load, kg (lb)	Weight/ length,* g/cm (lb/in.)
Inconel, 304L, or 21-6-9	Glass	3.18 (1.25)	0.008 (0.003)	0.040 (0.016)	3,509 (7,735)	9.71 (0.0544)
	Boron	6.35 (2.50)	0.008 (0.003)	0.038 (0.015)	4,532 (9,992)	9.36 (0.0524)
	Graphite	3.18 (1.25)	0.008 (0.003)	0.038 (0.015)	4,281 (9,438)	8.04 (0.0450)
	PRD-49	3.18 (1.25)	0.008 (0.003)	0.040 (0.016)	3,891 (8,578)	7.93 (0.0444)
Aluminum	Glass	6.35 (2.50)	0.023 (0.009)	0.040 (0.016)	3,637 (8,019)	9.75 (0.0546)
	Boron	12.7 (5.00)	0.023 (0.009)	0.038 (0.015)	3,415 (7,528)	9.39 (0.0526)
	Graphite	6.35 (2.50)	0.023 (0.009)	0.038 (0.015)	4,560 (10,053)	8.07 (0.0452)
	PRD-49	6.35 (2.50)	0.023 (0.009)	0.040 (0.016)	4,047 (8,923)	3.61 (0.0446)
Titanium	Glass	6.35 (2.50)	0.015 (0.006)	0.040 (0.016)	3,021 (6,660)	10.02 (0.0561)
	Boron	12.7 (5.00)	0.015 (0.006)	0.038 (0.015)	2,851 (6,286)	9.66 (0.0541)
	Graphite	6.35 (2.50)	0.015 (0.006)	0.038 (0.015)	4,158 (9,167)	8.34 (0.0467)
	PRD-49	6.35 (2.50)	0.015 (0.006)	0.040 (0.016)	3,587 (7,907)	8.23 (0.0461)

Note:
1. Cylinder diameter is 20 cm (8.0 in.)
2. Internal pressure is 10.1 N/cm^2 (14.7 psi) for all cases
3. Approximate weight for all-metal cylinder is 45.6 g/cm (0.255 lb/in.)
4. *Composite weight data includes vacuum jacket liner and overwrap weight. Total line weight would include inner line, end fittings, standoffs, and end closures.

End closures: Three end closure concepts were evaluated: (1) stiff end closure with a convolute in the vacuum jacket to accommodate thermal expansion and contraction, (2) flexible end closure, capable of accommodating inner line expansion and contraction without relying on the vacuum jacket convolutes; and (3) stiff end closure and stiff vacuum jacket i.e., both end closure and vacuum jacket are designed to withstand the loads resulting from inner line expansion and contraction. Structural analysis showed concept 3 to be not feasible except for very short lines where the inner line expansion and contraction is small. Thermal analysis showed that concept 2, using a very thin metallic membrane 0.008 to 0.013 cm (0.003 to 0.005 in.) reinforced structurally with glass-fibers, would significantly reduce heat leakage through the end closure. This concept, however, would require development beyond the program schedule and cost limitations. Concept 1 was selected for all designs except the tension membrane. Structural and thermal analysis of end closures are provided in Appendix A and C, respectively.

Standoffs: The standoff provides lateral support between the inner line and the vacuum jacket. The key design objectives include minimum weight, thermal efficiency, and fabrication ease. A glass-fiber I-section standoff configuration was selected as best satisfying all design objectives. Structural analysis showed that standoffs are required at 30 and 61 cm (12 and 24 in.) intervals for the 20 and 46 cm (8 and 18 in.) vacuum jackets, respectively.

Vacuum acquisition and monitoring ports: Two possible locations were considered for vacuum acquisition ports: (1) the vacuum jacket barrel section, and (2) the end closure, shown in Figure 2. The end closure location was selected for the composite vacuum jackets because it provides a heavy section for welding and results in a smooth jacket surface which is less susceptible to damage. For the tension membrane vacuum jacket, the vacuum port was welded into one of the internal hoop support rings.

Design Concept Configurations. - Using the selected inner line, vacuum jacket, end closures, standoff, vacuum acquisition and monitoring ports, four composite vacuum jacketed line concepts and one tension membrane vacuum jacketed concept was developed. The configurations of these concepts are depicted in Figures 3 through 7.

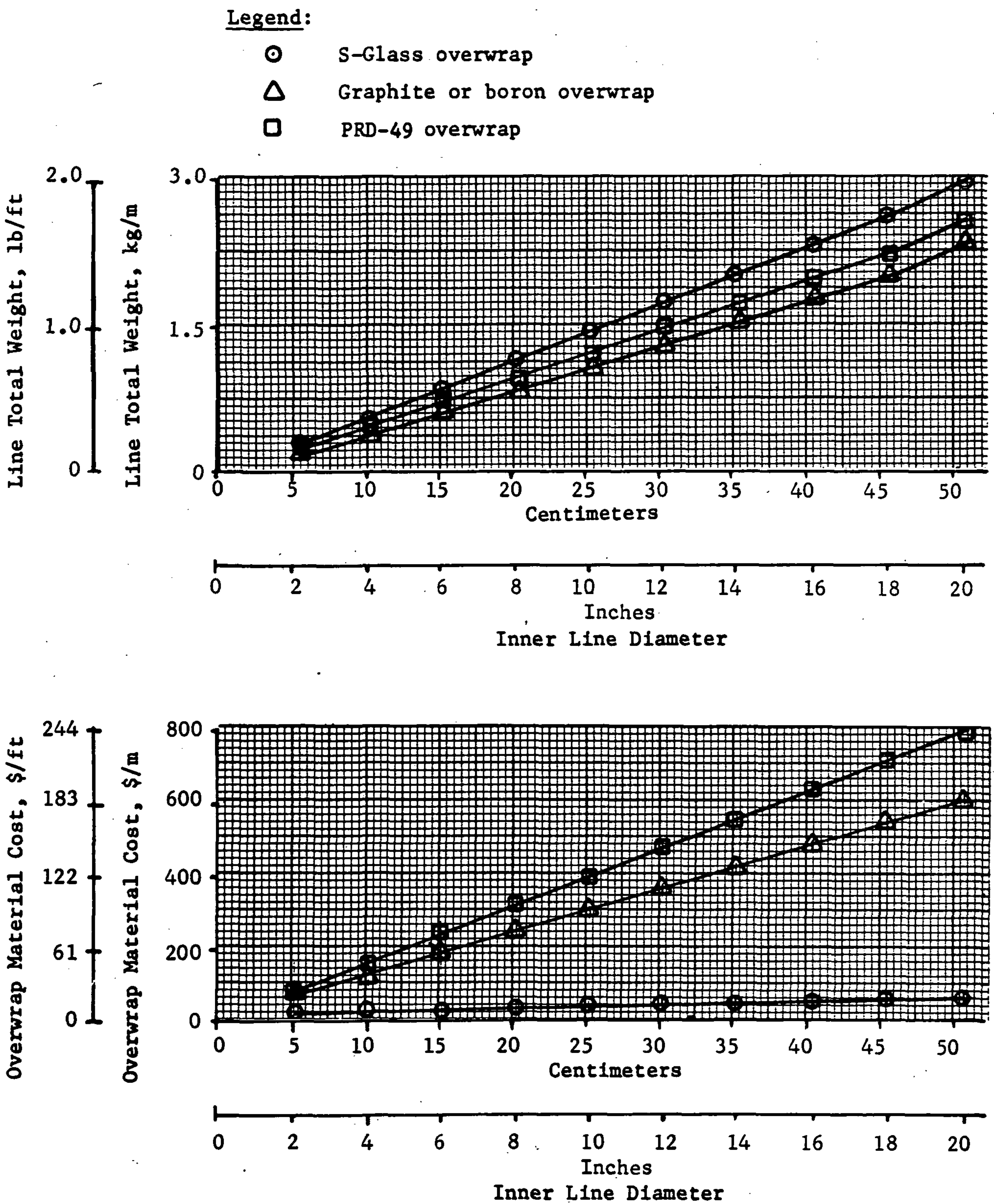


Figure 1. - Comparison of Overwrap Weight and Cost Per Unit Length Versus Inner Line Diameter

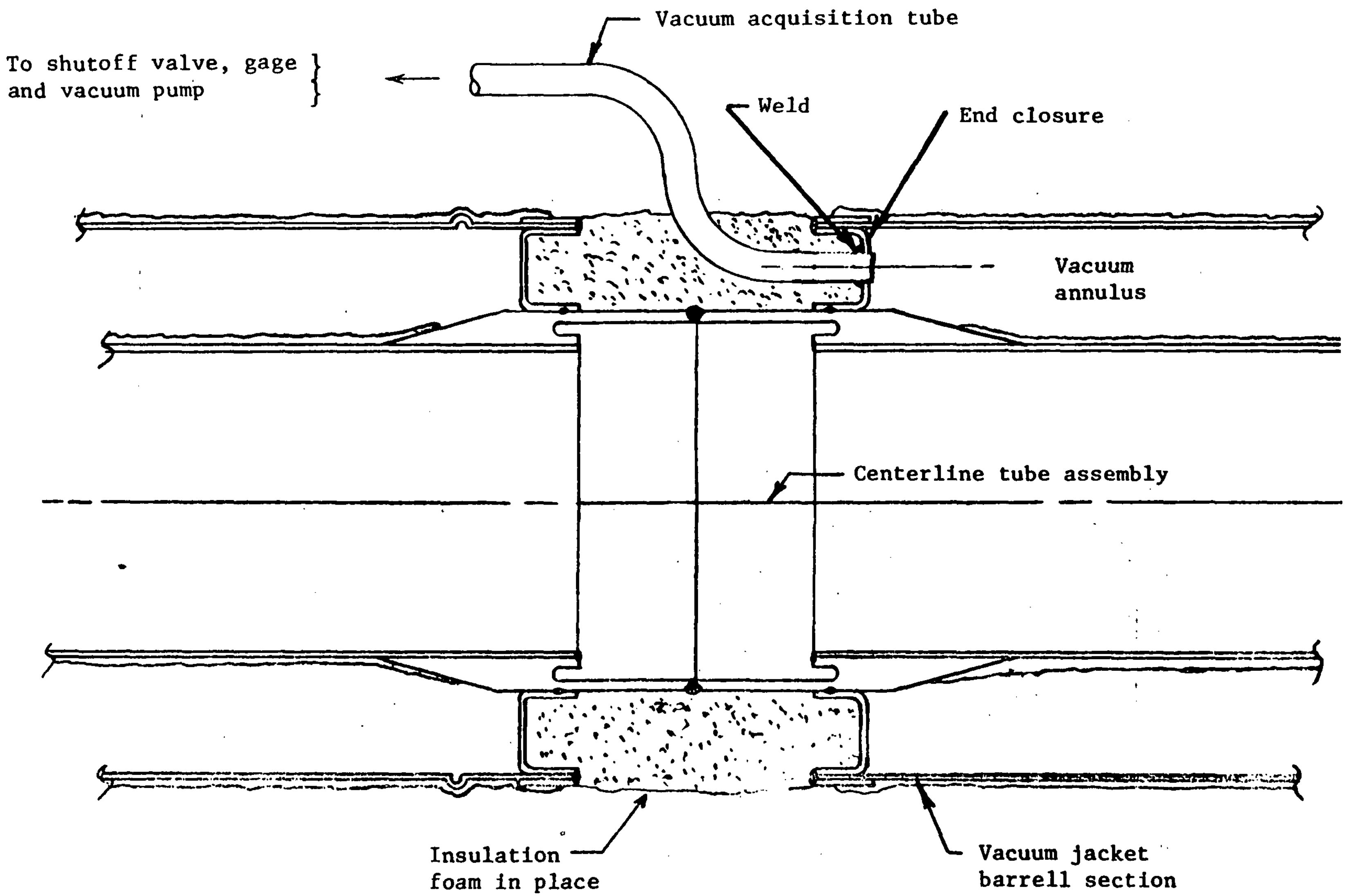


Figure 2. - Vacuum Acquisition Port

Unit	Dia	A	B	C	D	E	F	G	H	I	J
cm	13	59.0	61.0	0.163	0.328	0.109	0.023	0.008	0.023	3.871	0.051
in.	5	23.25	24	0.064	0.129	0.043	0.009	0.003	0.009	1.524	0.020

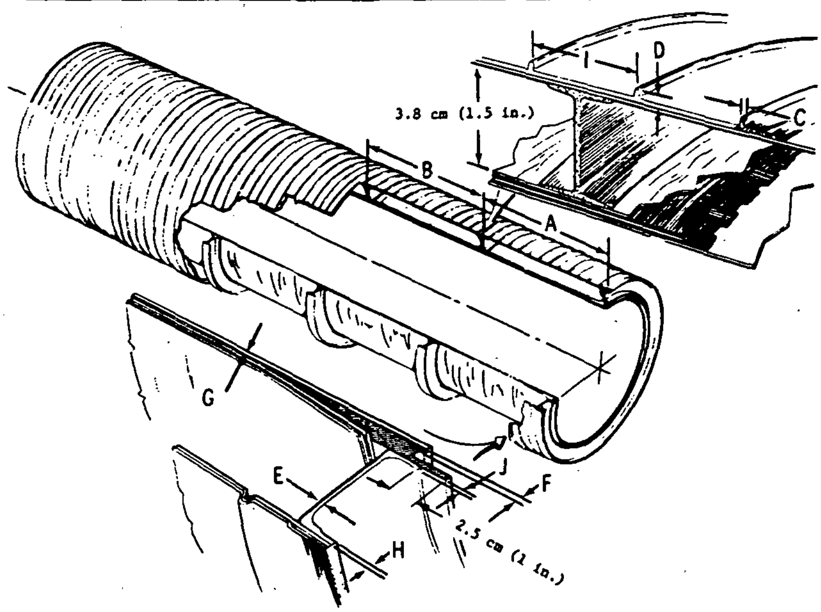


Figure 3. - Vacuum Jacketed Composite Line, Concept 1 (O.D. Glass Ribs)

Unit	Dia	A	B	C	D	E	F	G	H	I	J
cm	13	59.06	61.0	0.516	0.259	0.109	0.023	0.008	0.023	3.871	0.051
in.	5	23.25	24	0.203	0.102	0.043	0.009	0.003	0.009	1.524	0.020
cm	38	28.58	30.5	0.561	0.279	0.127	0.038	0.013	0.038	2.570	0.051
in.	15	11.25	12	0.221	0.110	0.050	0.015	0.005	0.015	1.012	0.020

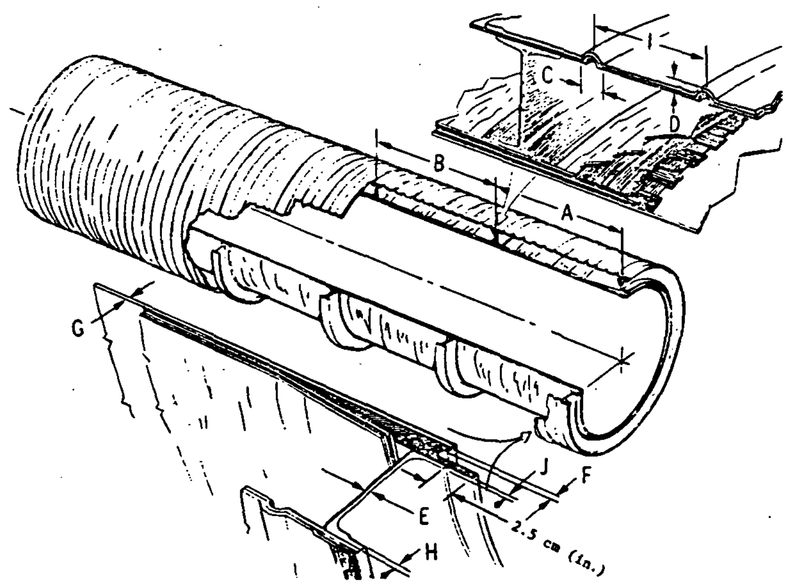


Figure 4. - Vacuum Jacketed Composite Line Concept 2 (Outside Convolute Stiffeners)

Unit	Dia	A	B	C	D	E	F	G	H	I	J
cm	39	28.58	30.5	0.137	0.274	0.127	0.036	0.013	0.038	2.578	0.051
in.	15	11.25	12	0.054	0.108	0.050	0.015	0.005	0.015	1.015	0.020

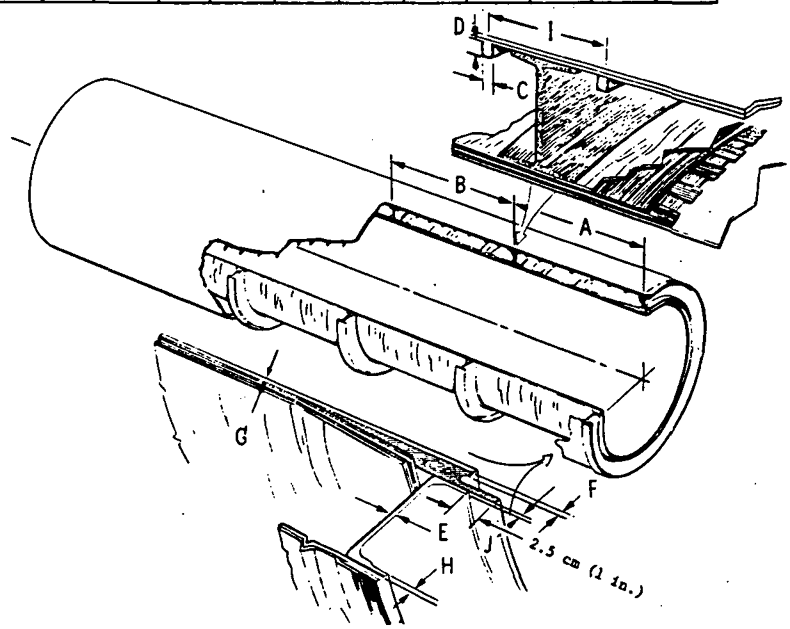


Figure 5. - Vacuum Jacketed Composite Line, Concept 3
(Internal Supports No Convolutes)

Unit	Dia	A	B	C	D	E	F	G	H
cm	13	59.06	61.0	3.871	0.109	0.023	0.051	0.008	0.023
in.	5	23.25	24	1.524	0.043	0.009	0.020	0.003	0.009

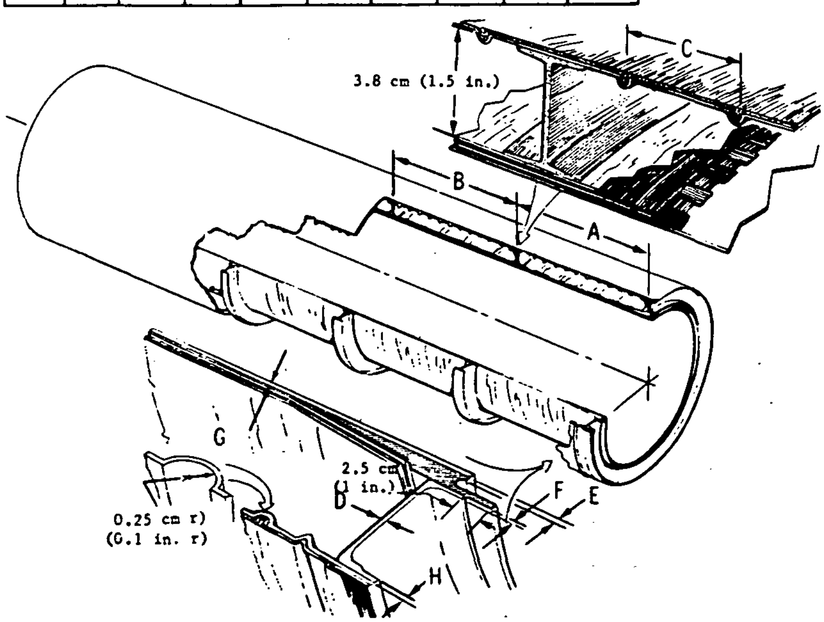


Figure 6. - Vacuum Jacketed Composite Line, Concept 4
(I.D. Convolutes with External Glass)

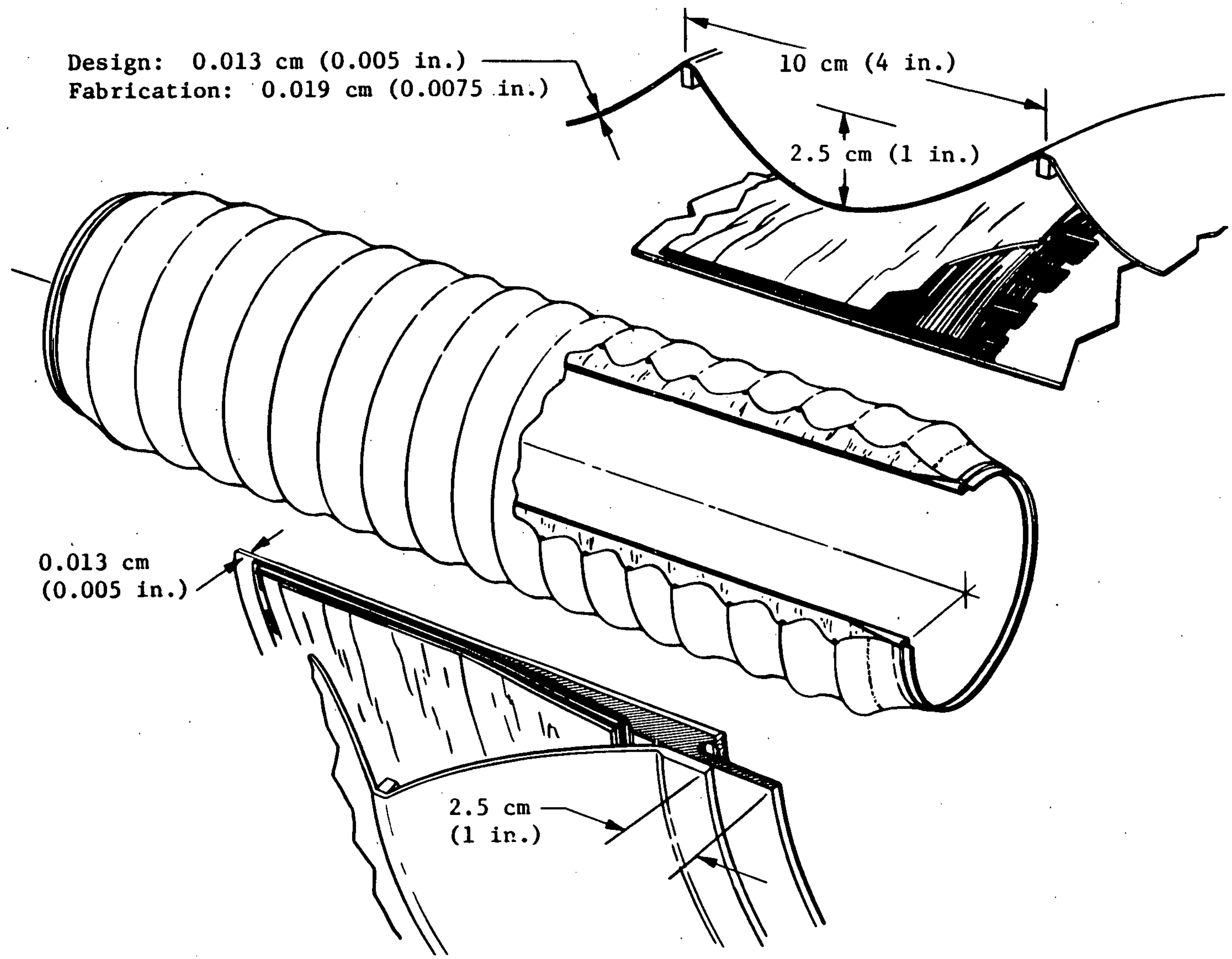


Figure 7. - Vacuum Jacketed Composite Line, Concept 5
(Tension Membrane)

CONCEPT EVALUATION

Structural, dynamics, weight, and cost analyses were performed for each of the six selected configurations. Results provided basic design data that were used in comparing the relative merits of each concept.

Structural Analysis of Composite Vacuum Jackets. - Results of the vacuum jacket structural analysis are based on the assumption that a perfect bond would exist between the metal liner and the overwrap, and that the overwrapped line would act as a true composite structure in resisting external pressure loading. It was found during test (discussed later) that a good bond was not achieved and it was necessary to increase the metal liner thickness to withstand external pressure loading.

Assuming a constant 3.8 cm (1.5 in.) annulus space between the vacuum jacket and the inner line, 13, 20, 33, 46 and 58 cm (5, 8, 13, 18 and 23 in.) diameter vacuum jackets up to 610 cm (240 in.) long were analyzed to determine circumferential stiffener dimensions, standoff dimensions and spacing for minimum weight. Each concept is designed to withstand an external collapse pressure of 25.3 N/cm^2 (36.7 psi).

The vacuum jacket structural loading consists of compressive load caused by thermal contraction of the inner line, reaction of pressure on the end closure, and bending due to launch loads and dynamic response. It was assumed that the vacuum jacket and end closure design concepts are such that load due to thermal contraction of the inner line is held to a minimum, and pressure on the end closure is reacted primarily by the inner line. Axial load caused by launch loads and dynamic response was checked to assure that stability is maintained with an applied pressure of 10.1 N/cm^2 (14.7 psi) and maximum anticipated axial load.

For a particular vacuum jacket composite layup configuration, the required spacing between circumferential stiffeners was calculated to assure that the composite structure between hoop stiffeners remains structurally stable up to an applied pressure of 25.3 N/cm^2 (36.7 psi).

For an assumed number of standoffs, the size of the hoop stiffeners was calculated so that the cylindrical section between standoffs remains structurally stable up to a pressure loading of 25.3 N/cm^2 (36.7 psi). The total system weight was then calculated and the number of standoffs was varied to determine the number that results in minimum structural system weight.

The structural concepts investigated are shown in Figure 8. The between-stiffener layup is identical for each concept because the minimum gage layup was found to be adequate. The layup con-

sists of a minimum gage 304L stainless steel liner [0.008 cm (0.003 in.) thick for 20 cm (8 in.) diameter jacket and 0.013 cm (0.005 in.) thick for 46 cm (18 in.) diameter jacket], a 0.040 cm (0.016 in.) thick hoop wrap of unidirectional S-Glass/epoxy and a 0.010 cm (0.004 in.) thick layer of S-Glass/epoxy 90-10 glass cloth with 90% of the fibers oriented in the axial direction.

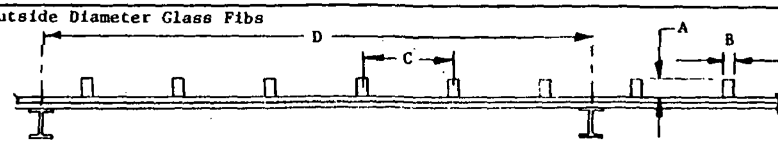
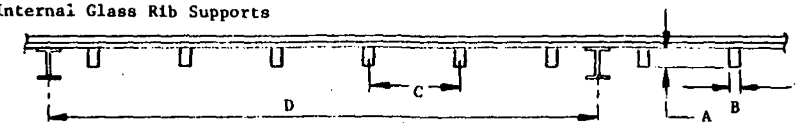
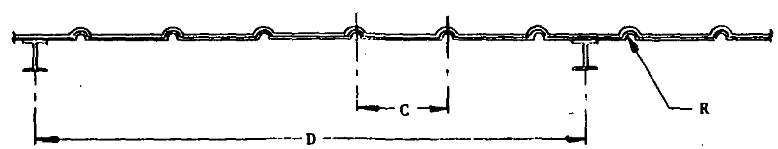
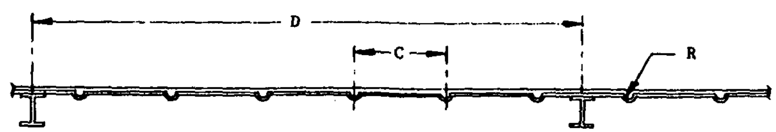
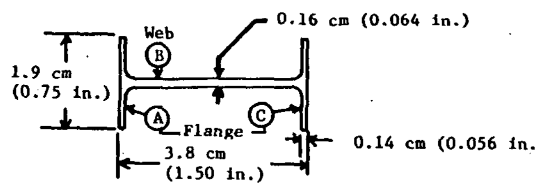
The collapse stability of the vacuum jackets with different stiffener and standoff spacing was investigated using the HOLBOAT (Holston's Buckling of Anisotropic tubes) computer program. The hoop stiffeners were assumed to act as a smeared layer of hoop wrap with no axial stiffness and only a local hoop stiffness. The stiffener spacing was first determined by changing the input length of the short cylinder between stiffeners until the critical buckling pressure of 25.3 N/cm^2 (36.7 psi) was obtained. The number of standoffs was then varied from 1 to 39 with the hoop stiffener resized for each standoff spacing so that the critical buckling pressure is 25.3 N/cm^2 (36.7 psi).

Total vacuum jacket weight versus number of standoffs was then plotted for each design concept and each diameter line. The results of this analysis depicting the minimum weight configuration for each concept is shown in Table V.

The capability of vacuum jacket design concepts 1, 3 and 4 to withstand combined external pressure and axial compression loading is shown in Figure 9. The 20 cm (8 in.) diameter and 46 cm (18 in.) diameter jackets will each withstand 25.3 N/cm^2 (36.7 psi).

Thermal contraction of the inner line could load the vacuum jacket in axial compression if the end annulus and vacuum jacket are rigid. The load level can be approximated by assuming that the metal in the inner line and vacuum jacket contributes most of axial stiffness and coefficient of thermal expansion. Using this assumption, axial compressive loads of 1014 kg (2230 lb) and 3880 kg (8530 lb) can be expected in the 20 cm (8 in.) and 46 cm (18 in.) vacuum jackets, respectively. It is obvious that it would be desirable to select a structural concept which allows only minimal transfer of load to the vacuum jacket due to inner line thermal contraction. This was done by including at least one low stiffness convolute in each of the vacuum jacket design concepts.

TABLE V.

Concept number and description	Dimension
1. Outside Diameter Glass Fibs 	Inside line diameter cm (in.)
	5.08 (2)
	12.70 (5)
3. Internal Glass Rib Supports 	25.40 (1C
	25.40 (1C
	38.10 (15
	50.80 (2C
2. External Convolute Stiffeners, Wrapped with S-Glass 	Inside line diameter cm (in.)
	5.08 (2)
	12.70 (5)
	25.40 (1(
	25.40 (1(
	38.10 (1!
	50.80 (2(
4. Internal Convolute Stiffeners, Filled with S-Glass 	Inside line diameter cm (in.)
	5.08 (2
	12.70 (5
	25.40 (1(
	25.40 (1(
	38.10 (1!
	50.80 (2(
Standoff Support Geometry 	Material:
	A & C
	1 layer a
	1 layer a
	3 layers
	1 layer a
	1 layer a

FOLDOUT FRAME

FOLDOUT FRAME

TABLE V. - VACUUM JACKET DESIGN DETAILS SUMMARY

Dimensions							
Inside line diameter cm (in.)	Vacuum jacket diameter cm (in.)	A cm (in.)	B cm (in.)	C cm (in.)	D cm (in.)	Composite thickness cm (in.)	Liner thickness cm (in.)
5.08 (2)	12.70 (5)	0.34 (0.14)	0.17 (0.07)	9.04 (3.56)	101.60 (40)	0.05 (0.020)	0.008 (0.003)
12.70 (5)	20.32 (8)	0.35 (0.14)	0.18 (0.07)	4.98 (1.96)	60.96 (24)	0.05 (0.020)	0.008 (0.003)
25.40 (10)	33.02 (13)	0.39 (0.16)	0.20 (0.08)	3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
25.40 (10)	33.02 (13)	0.39 (0.16)	0.20 (0.08)	3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
38.10 (15)	45.72 (18)	0.38 (0.15)	0.19 (0.08)	2.79 (1.10)	30.48 (12)	0.05 (0.020)	0.013 (0.005)
50.80 (20)	58.42 (23)	0.39 (0.16)	0.20 (0.08)	2.34 (0.92)	25.40 (10)	0.05 (0.020)	0.013 (0.005)
Inside line diameter cm (in.)	Vacuum jacket diameter cm (in.)	Radius-R cm (in.)		C cm (in.)	D cm (in.)	Composite thickness cm (in.)	Liner thickness cm (in.)
5.08 (2)	12.70 (5)	0.28 (0.11)		9.04 (3.56)	101.60 (40)	0.05 (0.020)	0.008 (0.003)
12.70 (5)	20.32 (8)	0.29 (0.11)		4.98 (1.96)	60.96 (24)	0.05 (0.020)	0.008 (0.003)
25.40 (10)	33.02 (13)	0.34 (0.13)		3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
25.40 (10)	33.02 (13)	0.34 (0.13)		3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
38.10 (15)	45.72 (18)	0.30 (0.12)		2.79 (1.10)	30.48 (12)	0.05 (0.020)	0.013 (0.005)
50.80 (20)	58.42 (23)	0.31 (0.12)		2.34 (0.92)	25.40 (10)	0.05 (0.020)	0.013 (0.005)
Inside line diameter cm (in.)	Vacuum jacket diameter cm (in.)	A cm (in.)		C cm (in.)	D cm (in.)	Composite thickness cm (in.)	Liner thickness cm (in.)
5.08 (2)	12.70 (5)	0.25 (0.10)		9.04 (3.56)	101.60 (40)	0.05 (0.020)	0.008 (0.003)
12.70 (5)	20.32 (8)	0.26 (0.10)		4.98 (1.96)	60.96 (24)	0.05 (0.020)	0.008 (0.003)
25.40 (10)	33.02 (13)	0.29 (0.12)		3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
25.40 (10)	33.02 (13)	0.29 (0.12)		3.02 (1.19)	40.64 (16)	0.05 (0.020)	0.013 (0.005)
38.10 (15)	45.72 (18)	0.27 (0.11)		2.79 (1.10)	30.48 (12)	0.05 (0.020)	0.013 (0.005)
50.80 (20)	58.42 (23)	0.28 (0.11)		2.34 (0.92)	25.40 (10)	0.05 (0.020)	0.013 (0.005)

Material: S-Glass in 58-68R Resin

A & C Flange Layup:

rad (deg)	cm (in.)
1 layer at + 0.78 (45)	layer thickness: 0.02 (0.008)
1 layer at - 0.78 (45)	layer thickness: 0.02 (0.008)
3 layers at 1.57 (90)	layer thickness: 0.06 (0.024)
1 layer at + 0.78 (45)	layer thickness: 0.02 (0.008)
1 layer at - 0.78 (45)	layer thickness: 0.02 (0.008)
	Total thickness: 0.14 (0.056)

B Web Layup:

rad (deg)	cm (in.)
1 layer at + 0.78 (45)	layer thickness: 0.02 (0.008)
1 layer at - 0.78 (45)	layer thickness: 0.02 (0.008)
4 layers at 1.57 (90)	layer thickness: 0.08 (0.032)
1 layer at + 0.78 (45)	layer thickness: 0.02 (0.008)
1 layer at - 0.78 (45)	layer thickness: 0.02 (0.008)
	Total thickness: 0.16 (0.064)

FOLDOUT FRAME 2

FOLDOUT FRAME 3

Dynamic Analysis of Composite Vacuum Jacketed Lines. - The purpose of the dynamic analysis was to determine the response of the jacketed composite lines to the predicted Shuttle environments and to ascertain whether or not these responses are excessive and would prevent the use of the selected concepts on a Space Shuttle.

Dynamic models: The dynamic model is an analytical representation of the vacuum jacketed composite line. The intent of the model is to emulate physical properties of the system (stiffness, mass, and boundary conditions) in such a way as to yield the best analytical representation of the true system.

The basic model consists of two parallel 6.1 m (20 ft) beams, simulating the concentric (parallel) inner line and the vacuum jacket, each having cross-sectional properties representative of the actual tubes. Shell modes were determined to be in an appreciably higher frequency range than the bending modes and, therefore, were neglected in the model and loads analyses. The section properties used for the various line configurations and vacuum jacket diameters are based on wall thickness of 0.008 cm (0.003 in.) Inconel, and 0.051 cm (0.020 in.) S-Glass for diameters up to 25.4 cm (10 in.) and 0.013 cm (0.005 in.) Inconel, and 0.051 cm (0.020 in.) S-Glass for diameters greater than 25 cm (10 in.). In addition, the vacuum jackets were stiffened radially.

The basic boundary condition was designed to simulate the end fittings and represents a hinged end structure that will allow relative rotation of the two beams, but no relative displacement (lateral or longitudinal). In addition to the hinged ends, certain configurations were analyzed with external supports within the 6.1 m (20 ft) span; this will be discussed in detail later.

The final design parameters included in the model were the standoffs that separate the inner line and the vacuum jacket. These standoffs are modeled by rigidly tying together the lateral motions of the beams at regular intervals equal to the spacing of the standoffs. Thus, the beams are forced to translate together at these points and their rotations are still independent of each other. Although the standoff supports were designed to prevent the collapse of the jacket under external pressure, they serve an additional structural purpose, which will be discussed later.

Table VI delineates the details of the various configurations analyzed.

TABLE VI. - INNER LINE/VACUUM JACKET CONFIGURATIONS (DYNAMIC ANALYSIS)

Case no.	Diameter inner line, cm (in.)	Diameter vacuum jacket, cm (in.)	Metal thickness, cm (in.)	Standoff support spacing, cm (in.)	Number of external supports
1	5 (2)	13 (5)	0.008 (0.003)	61 (24)	1
2	13 (5)	20 (8)	0.008 (0.003)	61 (24)	
3	13 (5)	20 (8*)	0.008 (0.003)	61 (24)	
4	13 (5)	20 (8)	0.008 (0.003)	61 (24)	1
5	13 (5)	20 (8*)	0.008 (0.003)	61 (24)	2
6	25 (10)	33 (13)	0.008 (0.003)	61 (24)	1
7	25 (10)	33 (13)	0.013 (0.005)	30 (12)	1
8	38 (15)	46 (18)	0.013 (0.005)	30 (12)	
9	38 (15)	46 (18*)	0.013 (0.005)	30 (12)	
10	38 (15)	46 (18)	0.013 (0.005)	30 (12)	1
11	38 (15)	46 (18*)	0.013 (0.005)	30 (12)	2
12	51 (20)	58 (23)	0.013 (0.005)	30 (12)	1

*Convoluted

Vibration analysis: The objective of the vibration analysis was to determine the model properties (i.e., mode shapes, frequencies) for the various configurations, which in turn are used to predict system response to the Shuttle environments. An additional requirement, however, was that the natural frequencies of the lines be greater than 20 Hz. This requirement was imposed to assure that there would be no coupling between the vacuum jacketed lines and any possible pogo phenomena that may occur during a Shuttle flight.

Table VII details the natural frequencies for the fundamental modes of each of the systems. As can be seen from the data, vacuum jacketed line systems with no intermediate supports within the 6.1 m (20 ft) span did not meet the 20 Hz requirement. This was especially true of lines with convoluted vacuum jackets, since the convolutes represent small bending elements in the jacket wall, tend to reduce the stiffness, and subsequently the system natural frequencies. As a result of this data, developed for the 13 and 38 cm (5 and 15 in.) diameter inner lines, unsupported cases were ruled out for the other line sizes. One or two external supports over the 6.1 m (20 ft) span, were added as required to keep the frequency above the 20 Hz minimum.

Loads analysis: A review of Shuttle dynamic environments, such as steady-state acceleration, flight transients, and random excitation, revealed that governing criteria for the vacuum jacketed lines is the random vibration environment. Therefore, the loads analyses consisted of determining the response of the lines to the applicable random vibration environment shown in Figure 10, using the previously determined model properties.

The technique employed was to analytically subject the lines to the input spectrum presented in Figure 10, and to determine the 3σ bending moments and deflections. Only the overall line deflections were calculated, since the standoff supports eliminate the rattlespace problem between the inner line and the vacuum jacket.

In performing the analyses to determine the 3σ bending moments, only the nonconvolute jacket configurations were considered for the reason that the higher frequency nonconvolute lines will experience higher accelerations, and subsequently higher bending moments, than the corresponding lines with convolutes. (This is based on the fact that higher frequency systems experience greater acceleration responses in a random vibration environment.) Since the nonconvolute line bending moments are greater, they represent the worst case and are conservative for use on the convoluted systems. The convolutes do not affect the stress levels in the vacuum jackets and for a given moment both the convoluted and nonconvoluted vacuum jacket will have the same bending stress. In other words, the convolutes do not affect the vacuum jacket structural response. The results of the loads analysis for the various configurations are shown in Table VIII.

Table VII. - FUNDAMENTAL FREQUENCIES OF LINE CONFIGURATIONS

Case no.	Lateral frequency, Hz	Number of external supports
1	23.07	1
2	7.97	
3	4.39	
4	31.77	1
5	33.30	2
6	27.68	1
7	51.03	
8	15.94	
9	10.58	
10	62.91	1
11	65.07	2
12	74.85	1

*Case numbers are defined in Table VI.

TABLE VIII. - VACUUM JACKETED COMPOSITE LINES, MAXIMUM 3 σ DEFLECTION AND 3 σ BENDING MOMENTS

Case* no.	Maximum 3 σ deflection cm (in.)	Inner line-maximum 3 σ bending moments N-m (in.-lb)	Vacuum jacket-maximum 3 σ bending moments N-m (in.-lb)
1	0.94 (0.371)	26.2 (232)	409 (3,620)
2	4.44 (1.748)	239 (2,115)	954 (8,442)
3	7.76 (3.057)	Not Computed	Not Computed
4	0.68 (0.268)	292 (2,580)	1,168 (10,340)
5	0.90 (0.356)	Not Computed	Not Computed
6	0.78 (0.307)	609 (5,391)	2,681 (23,730)
7	0.35 (0.136)	1,686 (14,920)	2,499 (22,120)
8	2.21 (0.872)	4,209 (37,250)	7,760 (68,680)
9	3.36 (1.324)	Not Computed	Not Computed
10	0.25 (0.098)	3,848 (34,060)	7,099 (62,830)
11	0.34 (0.133)	Not Computed	Not Computed
12	0.19 (0.076)	7,554 (66,860)	11,580 (102,500)

*Case numbers are defined in Table VI.

TABLE IX. - UNIT COST COMPARISON, 61 cm (24 in.) LONG LINE†

Concept (Figs. 3 thru 7)	Inner Line Diameter, 13 cm (5 in.)	Inner Line Diameter 38 cm (15 in.)
1	$ 1590	$ 3450
2	$ 1655	$ 3587
3	$ 1670	$ 3698
4	$ 1675	$ 3685
5	--	$ 8215

†Unit costs are based on a quantity of 2 units.

Conclusions: From these analyses we conclude that 6.1 m (20 ft) unsupported spans, whether convoluted or nonconvoluted, are not acceptable within the limits of the 20-Hz minimum requirement, and that intermediate supports are required.

Stress analyses indicate that the bending moments computed for both the inner line and the vacuum jackets are at acceptable levels for Shuttle applications. The deflections computed have not been evaluated in terms of acceptability since this depends on design details of a Shuttle configuration and the proximity of the lines to the spacecraft, but appear to be in an acceptable range.

Structural and Dynamic Analyses of Tension Membrane Vacuum Jacket. These analyses were performed by the Grumman Aerospace Corporation and are included in this report in Appendix E. The results of these analyses are summarized in the following paragraphs.

Structural analysis: The tension membrane shell consists of a series of toroidal segments that carry load to intermediate rings in suspension bridge fashion. Unlike sandwich and discrete stiffener cylinder designs, the membrane shell is loaded in tension, and thus the material can operate at a stress close to its yield point. The compact intermediate compression rings carry the transverse component of the membrane load and are designed from overall and local instability considerations. Although material is used at a high efficiency in the membrane shell, it is not able to sustain longitudinal loads unless supported at its ends. In application to vacuum jacketed lines, it is convenient to use the inner line to support the tension membrane shell ends.

The key assumption in the formulation of the tension membrane shell theory is that the membrane is permitted to buckle hoopwise with the pressure load being carried along the meridian direction. This expected physical behavior can be incorporated into the analysis in one of two ways:

1) assume that the hoop stress resultant is equal to zero, or

2) analyze the membrane as an orthotropic shell with its circumferential modulus of elasticity small compared to its meridional modulus.

If the annulus, between the outer shell and the pressure vessel is specified, then for a given membrane depth, a design exists for each ring spacing, and weight, per unit length of outer shell can be computed. As the ring spacing decreases, the r_1, radius of curvature of the membrane decreases, and the required jacket thickness is reduced. With the skin at minimum thickness, ring spacings were further decreased beyond the minimum weight point to reduce

the axial load produced by the membrane for reasons of compatibility with the inner line design. The inner line design placed a maximum compressive limit load on the LH_2 line to 175 N/cm (100 lb/in.) of circumference. This load was achieved by holding the sag of the catenary constant while decreasing the ring spacing. From a dynamic (vibration) viewpoint, such designs of increased flexibility exhibit high flexural stresses. To reduce the flexibility and flexural stresses, the final design maintains the same meridional radius of curvature (hence the same catenary tension) but reduces the sag by introducing flats over the rings.

Acoustic analysis: Requirements for the tension membrane test specimen include withstanding an acoustic noise level of 160 dB applied for 450 sec and 167 dB applied for 60 sec. The method of analysis used is depicted in Appendix E.

The analysis shows that the maximum dynamic stress will be 12,170 N/cm^2 (17,385 psi), sustained for approximately 26,000 cycles. The endurance limit for 321 stainless steel is 26,200 N/cm^2 (38,000 psi), indicating that the planned exposure is safe from a sonic fatigue consideration.

Lateral structural vibration of full tension membrane: A dynamic analysis of the tension membrane vacuum jacket was performed to determine its response to the required acceleration spectral density given in Figure 10. The fundamental natural frequencies, G levels, and displacements were determined for several unsupported jacket lengths. The effective jacket flexural stiffness for the analysis was obtained using the Grumman STARS (shells of revolution) computer program. The analysis incorporated both isotropic and orthotropic behavior of the membrane. For orthotropic behavior, the modulus of elasticity in the hoop direction was assumed to be equal to 10% of the modulus in the axial direction. This analysis is presented in Appendix E. The calculations show that the peak stress in the 0.010 cm (0.004 in.) steel membrane reaches 86,100 N/cm^2 (125,000 psi) at the edge of the ring for a 3.05 m (10 ft) support spacing and is somewhat lower for a 1.52 m (5 ft) spacing. A 6.10 m (20 ft) support spacing is unacceptable since the maximum deflection exceeds the clearance between the jacket and the inner line. For a 3.05 m (10 ft) support spacing and assuming an orthotropic membrane, a 3.02 cm (1.19 in.) jacket deflection coupled with a 0.203 cm (0.080 in.) line deflection leaves a sufficient gap remaining from a 3.80 cm (1.5 in.) initial gap.

If the strength of the steel membrane is not greater than the 86,100 N/cm^2 (125,000 psi) level, a small thickness increase will be required in the membrane in the vicinity of the rings.

It should be noted that the foregoing analysis takes no theoretical advantage of the longitudinal tension already existing to increase the stiffness of the membrane. At 6.10 m (20 ft) spans, this would be an important effect.

Longitudinal acceleration: The effect of longitudinal acceleration is to produce a tensile loading in the outer jacket, similar to the loading produced by pressure. Combining pressure and axial acceleration will produce an increase in the maximum tensile stress in the outer jacket. The effect of longitudinal acceleration, however, is small compared to the effect of pressure. The load due to external pressure is approximately 175 N/cm (100 lb/in.) and the load due to acceleration is 3.2 N/cm (1.8 lb/in.).

Weight Analysis. - Total vacuum jacketed line weights were calculated for line diameters up to 25 cm (10 in.) with an operating pressure of 42 N/cm^2 (60 psi) absolute and for line diameters over 25 cm (10 in.) with an operating pressure of 69 N/cm^2 (100 psi) absolute. The theoretical weights for each concept are given in Figures 11 and 12. Weights are presented for the tension membrane both in the overwrapped configuration and bare metal configuration because some protective cover may be required on the tension membrane to prevent damage for flight configuration. The weight calculations show that there is very little difference in weight between the design concepts considered.

Cost Analysis. - Fabrication costs using stainless steel and aluminum vacuum jacket liners were estimated for each of the selected design concepts based on the test specimen configuration. These costs are provided in Table IX.

Vacuum Acquisition and Maintenance. - Thermal performance of a vacuum jacketed line is a direct function of the vacuum level in the annulus. An advantage of a pre-evacuated line is that it is ready for use long before mission time since the pre-evacuation is carried out during fabrication. A disadvantage is that an extremely low leak rate is required of all components making up the vacuum jackets so that a preflight vacuum pump-down will not be necessary.

Whether or not the various concepts can be successfully pre-evacuated is directly related to the quality of the construction and the outgassing of nonmetallic materials in the vacuum annulus. All selected design concepts are considered to be pre-evacuated systems. For the tension membrane, this will serve to rigidize the specimen making handling and shipping easier.

Before sealing the vacuum annulus a preconditioning process should be carried out. This process should include (1) chemical cleaning of all components, (2) 100% x-ray inspection of all welds to ensure leak free welds, (3) helium leak check of the inner line, (4) bake-out at a specified temperature and for a specified time depending on the materials used, and (5) helium leak check of the outer jacket.

The desired level of sealed vacuum may not be maintained with some concepts, due to material applications or construction techniques. In this case, an internal vacuum pump can be installed in the line and can be operated continuously. This would replace ground pumping before flight and maintenance between missions. The simplicity and ruggedness of the magnetic ion pump make it most suitable for this application. Additionally, the pump can also be used as a vacuum gage by reading the current that it draws. This system is most commonly applied to systems with severe requirements, 10^{-2} N/cm^2 (10^{-4} torr) or lower.

Concept Evaluation Summary.- The evaluation of the various design concepts was performed before fabrication and testing of the specimens. The evaluation indicated that all concepts are structurally sound and capable of meeting anticipated Space Shuttle requirements. A comparison of the predicted weights showed that there is very little difference in weight between the various concepts, with the tension membrane having the lowest potential weight. A comparison of fabrication costs predicted that aluminum vacuum jackets would be significantly more expensive than steel. This conclusion is based on the assumption that the inner line is steel and that an aluminum to steel transition joint is required. The cost analysis also indicated that the tension membrane is more costly than the other concepts by a factor of 2+.

Based on the concept evaluation performed during the early phase of the program, none of the design concepts showed clear superiority over the others. The tension membrane was the least weight but also the most costly. One concept may be superior for specific mission requirements, depending upon parameter sensitivities, i.e., weight, cost, thermal performance, and loads. The design concepts were compared again after fabrication and testing of the test specimens were completed.

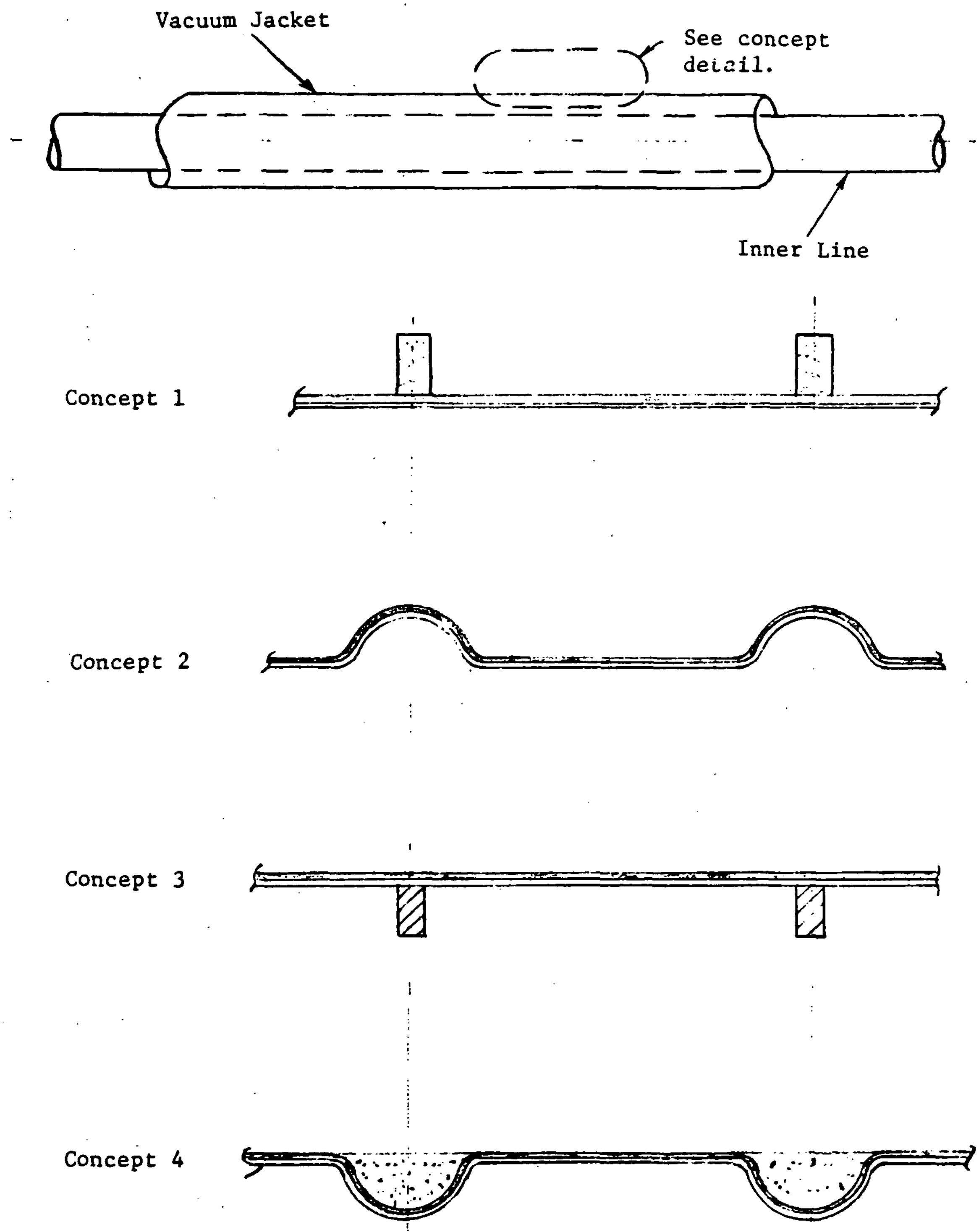


Figure 8. - Circumferential Stiffener Concepts

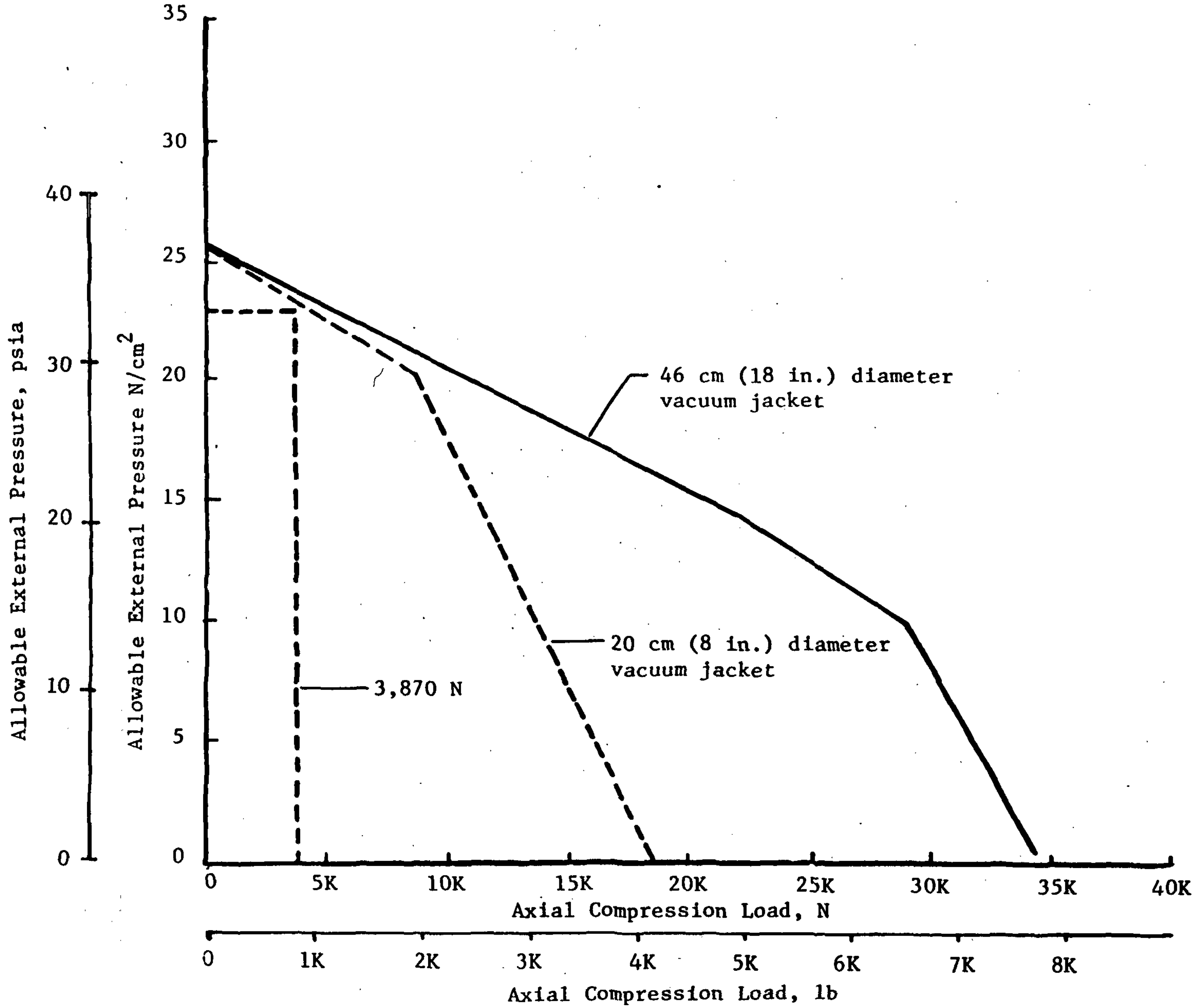


Figure 9. - Vacuum Jacket Axial Compression Loading Capability

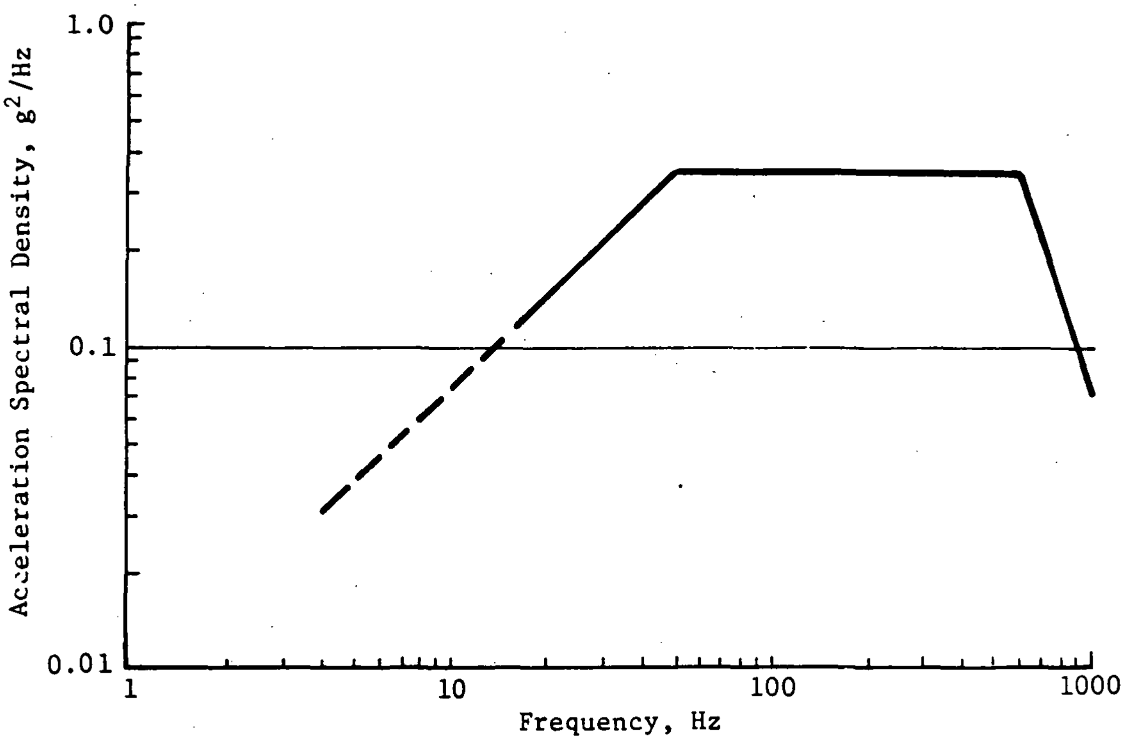


Figure 10. - Random Vibration Input (Shuttle Launch)

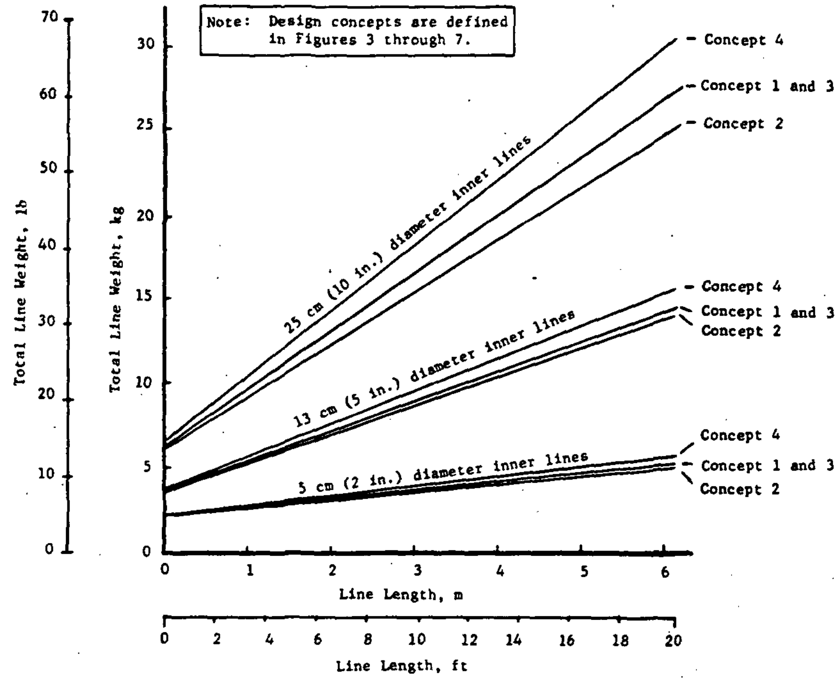


Figure 11. - Vacuum Jacketed Composite Line Weight [42 N/cm^2 (60 psi) Absolute Operating Pressure]

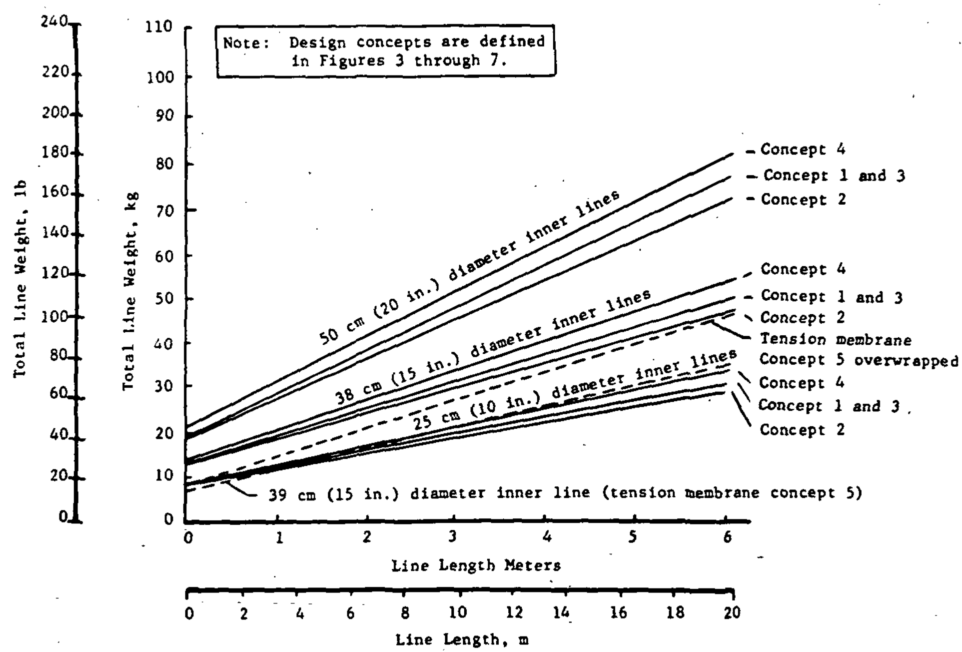


Figure 12. - Vacuum Jacketed Composite Line Weight [69 N/cm^2 (100 psi) Absolute Operating Pressure]

PRELIMINARY TESTING

A preliminary testing program was conducted to evaluate design and fabrication techniques planned for the program. Vacuum jacket structural integrity, bonding composite materials to metal liners and composite outgassing was evaluated. The following paragraphs discuss the testing that was performed and results.

Vacuum Shell Integrity Tests. - External pressure testing was conducted on two prototype composite vacuum jackets and the tension membrane vacuum jacket. The configuration of the composite vacuum jackets tested is defined by the design details in Table X. Each of the test specimens was placed in a pressure chamber, as shown in Figure 13, the vacuum annulus of the test specimen was evacuated, and the chamber was pressurized until the test specimen collapsed under external pressure. Failure was noted by a sudden change in vacuum annulus pressure. The first test specimens collapsed at a pressure differential of 19.8 N/cm^2 (28.7 psid), and the second, of a different design, at 45.3 N/cm^2 (65.7 psid). Both failed at 82% of theoretical collapse pressure. This correlation between theoretical and test actuals was considered acceptable and provided confidence in both the fabrication and analytical techniques used.

External pressure testing of the tension membrane vacuum jacket was performed by Grumman Aerospace Corporation with the tension membrane welded to a stainless steel dummy inner line. The vacuum annulus was evacuated to 0.03 N/cm^2 (0.05 psi) absolute and cycled back to ambient pressure nine times to verify structural integrity. Strain gage measurements were made during the pressure cycling and transformed into hoop and longitudinal stresses. Based on the material thickness of 0.019 cm (0.0075 in.) in the center bay (as determined by Vida gage after chem-milling), and assuming that all the load is carried longitudinally, the stress was calculated to be 5840 N/cm^2 (8470 psi). The yield stress of 321 annealed stainless steel is 24,000 to 31,000 N/cm^2 (35,000 to 45,000 psi) providing a factor of safety of:

$$FS = \frac{24,000}{5840} = 4.1$$

when the tension membrane is subjected to the external pressure loading of 10.1 N/cm^2 (14.7 psi). Additional details pertaining to tension membrane testing are provided in Appendix E.

Bonding Tensile Test. - Bonding tensile tests were performed to evaluate the bonding characteristics of the composite overwrap to the metal inner line and vacuum jacket liners. The tests were performed on one inch square bonded test coupons by pulling the coupons apart with a tensile testing machine. Test coupons were made using a thin sheet of Inconel 718 bonded to S-Glass (Epon 828-V40 resin) overwrap. The thin metallic liner was cleaned in

TABLE X.- DESIGN DETAILS - PRELIMINARY VACUUM JACKET TEST SPECIMENS

Design feature	First preliminary test specimen	Second preliminary test specimen	Tension membrane specimen
Design style	*External convolutes	†Internal hoop supports	§Tension membrane
Liner material	321 stainless steel	Inconel 718	321 stainless steel
Liner thickness	0.025 cm (0.010 in.)	0.025 cm (0.010 in.)	0.018 cm (0.007 in.)
Convolute or support spacing	3.18 cm (1.25 in.)	3.81 cm (0.50 in.)	15.14 cm (5.96 in.)
Convolute Radius	0.020 cm (0.08 in.)	N/A	N/A
Composite material	S-Glass (58-68R resin)	S-Glass (Epon 828-mpda)	N/A
Diameter	31 cm (12 in.)	26 cm (10.25 in.)	(50.2 cm) 19.8 in.
Length	31.8 cm (12.5 in.)	38 cm (15 in.)	63.5 cm (25 in.)
Overwrap pattern	1 hoop layer	±0.087 rad 2 layers (±5°) hoop	N/A
Calculated collapse pressure	24 N/cm^2 (35 psi) differential	55 N/cm^2 (80 psi) differential	>15.2 N/cm^2 (22 psi) differential

* Similar to concept 2
† Similar to concept 3
§ Concept 5

accordance with the procedure defined in the fabrication section of this report, and was bonded to the overwrap on one side and to 1.59 cm (0.625 in.) thick steel blocks on the other side using Hysol 934 adhesive. A photograph of a typical test coupon before and after testing is shown in Figure 14. Results of the testing are discussed in the following paragraphs.

Inconel 718 and S-Glass test coupons (58-68R resin system): The tensile coupons tested at ambient temperature had an average bond strength of 465 N/cm^2 (765 $lb/in.^2$). The highest value was 672 N/cm^2 (975 $lb/in.^2$) and the lowest value was 338 N/cm^2 (490 $lb/in.^2$). The loads were measured using a tensile machine with the load being applied at a rate of 2224 N/min (500 lb/min).

The tensile coupons tested at 97.2 (-285°F) had an average bond strength of 1324 N/cm^2 (1920 $lb/in.^2$). The highest value was 1482 N/cm^2 (2150 $lb/in.^2$) and the lowest value was 827 N/cm^2 (1200 $lb/in.^2$). These loads were measured using an Instron Model TTC Universal Tensile Test Machine with the load being applied at a rate of 0.05 cm (0.02 in.) per minute.

304 stainless steel and S-Glass test coupons (Epon 828 mpda resin system): The tensile tests were conducted at ambient temperature using a tensile machine with the loads being applied at 2224 N (500 lb) per minute. The coupons had an average bond strength of 374 N/cm^2 (543 $lb/in.^2$). The highest value was 493 N/cm^2 (715 $lb/in.^2$) and the lowest value was 183 N/cm^2 (266 $lb/in.^2$).

Failure mode: All of the test coupons failed at the Hysol adhesive interface and not at the bonded composite interface with the metal. Therefore, the actual bond strength of the composite to the metal liner was not determined but was shown to be greater than the values given above.

At this point in the program, it was believed that the criteria for a successful bond with adequate margin was 25.3 N/cm^2 (36.7 $lb/in.^2$), which provides a 2.5 safety factor for tension loading, as applied by external pressure. Of all the coupons tested, the lowest bond strength was 183 N/cm^2 (266 $lb/in.^2$), or a factor of 7.2 times the required strength. Thus, the need for more extensive testing and a more accurate determination of bond strength was not recognized. It was found later that bond strength in peel is also critical to the vacuum jacketed design. This is discussed in the Design and Fabrication sections.

Composite Outgassing Tests. - Testing was performed to determine the outgassing characteristics of S-Glass and 58-68R resin systems in a typical vacuum jacket annulus. Test samples were made from 1.90 cm (0.75 in.) diameter composite tubes that were overwrapped and cured to the same procedure as planned for the inner line of

the vacuum jacketed composite lines. Immediate indications from the testing were that composite postcuring would be required to reduce outgassing rates to acceptable levels. Samples of S-Glass and 58-68R resin composites were prepared and postcured as follows:

Specimen 1 - Postcured at a temperature of 413 K (285°F) and a vacuum of 10^{-3} N/cm^2 (10^{-5} torr) for 48 hours.

Specimen 2 - Postcured at a temperature of 413 K (285°F) and a vacuum of 10^{-3} N/cm^2 (10^{-5} torr) for 72 hours.

Vacuum thermal weight loss tests that involved continuously measuring the specimen weight in a vacuum were performed at ambient temperature for 72 hours. The results of these tests are plotted in Figures 15 and 16. Specimen 1 (48-hr postcure) experienced weight reduction for 54 hours and then stabilized, i.e., no further weight reduction was detected. Specimen 2 experienced weight loss for 12 hours with the major loss occurring in the first 2 hours of the test. The steep portion of this curve shows the specimen giving off moisture that had been absorbed after the postcure and before the start of the test. The dramatic difference in the two curves is an indication that the optimum postcure time is somewhere between 48 and 72 hours.

It was concluded from these tests that a 72-hour vacuum postcure would be required for the composite on the inner lines to assure capability to maintain a vacuum in the vacuum jacketed lines.

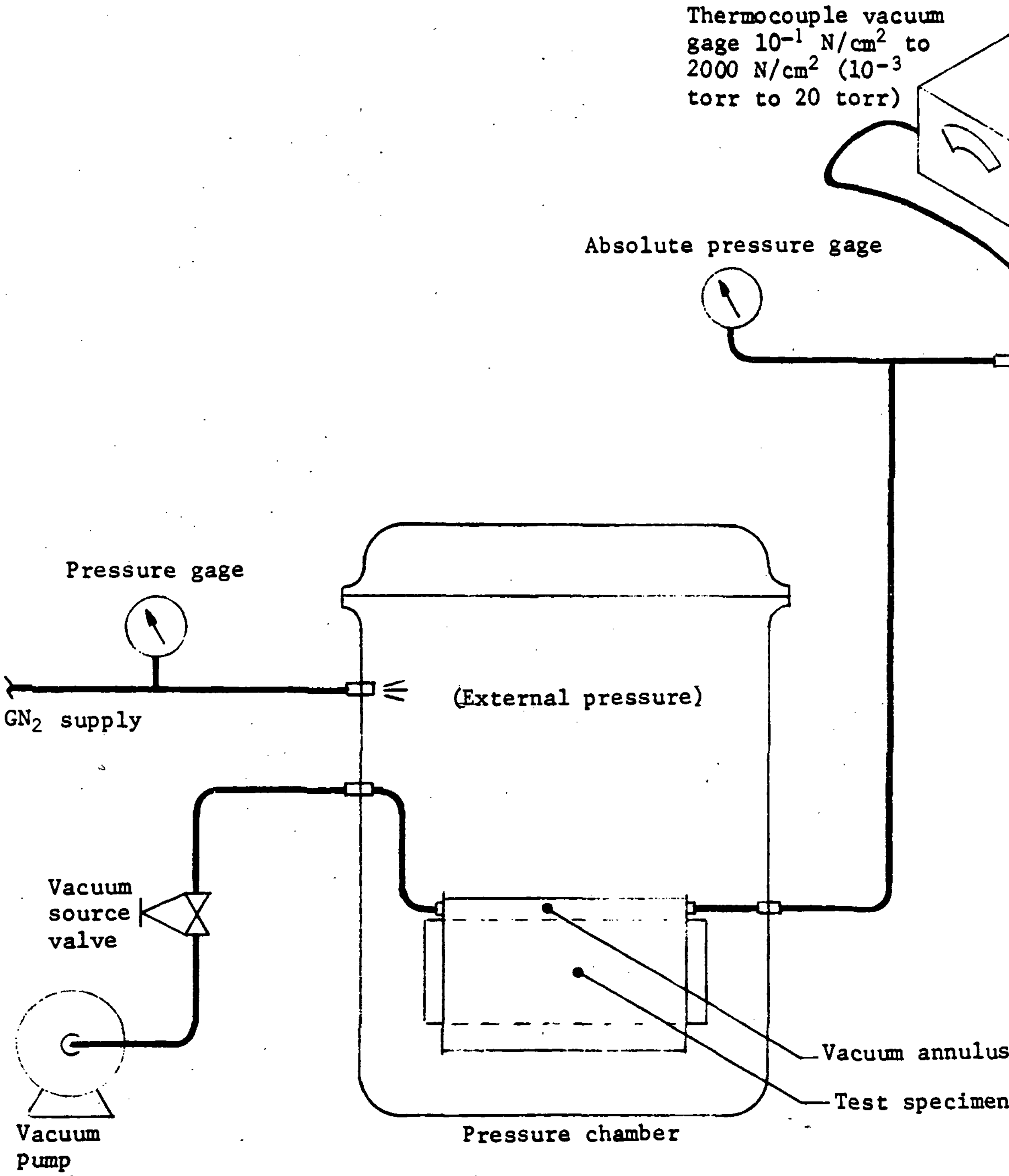


Figure 13.- Vacuum Shell Integrity Test Configuration

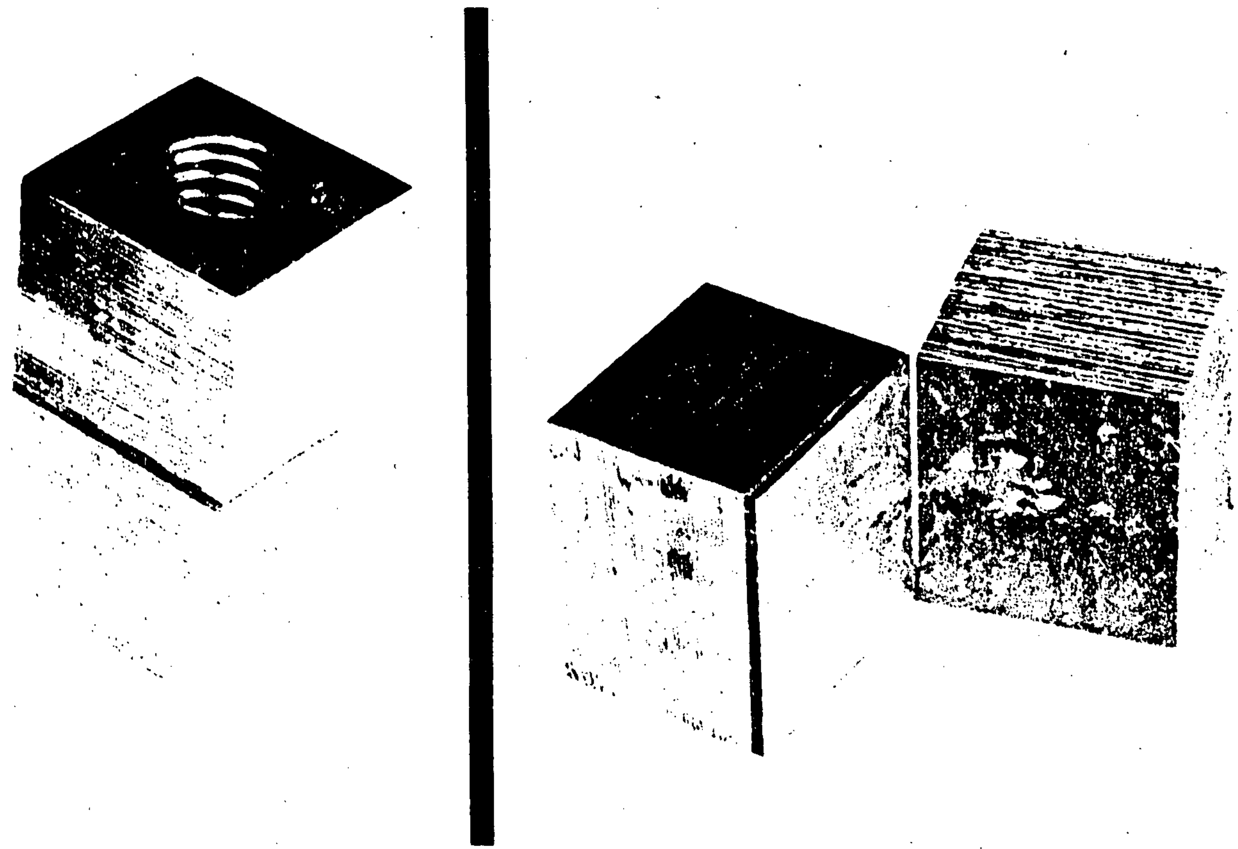


Figure 14.- Bond Tensile Test Specimen - Before and After Testing

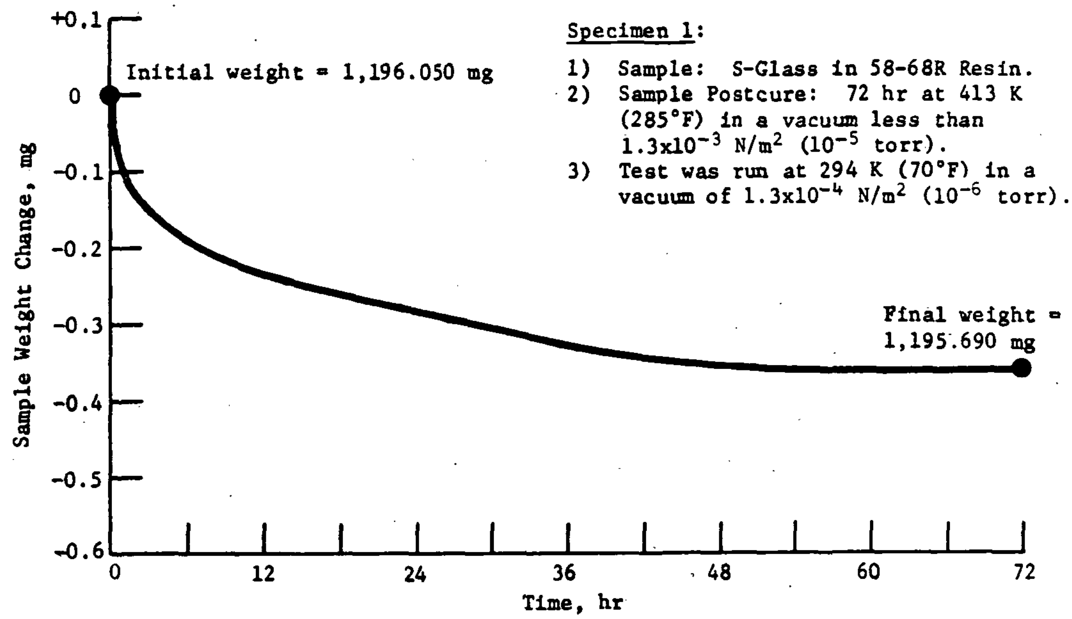


Figure 15.- Outgassing Test Results after Test Sample 1 Had Been Vacuum Postcured for 48 Hours

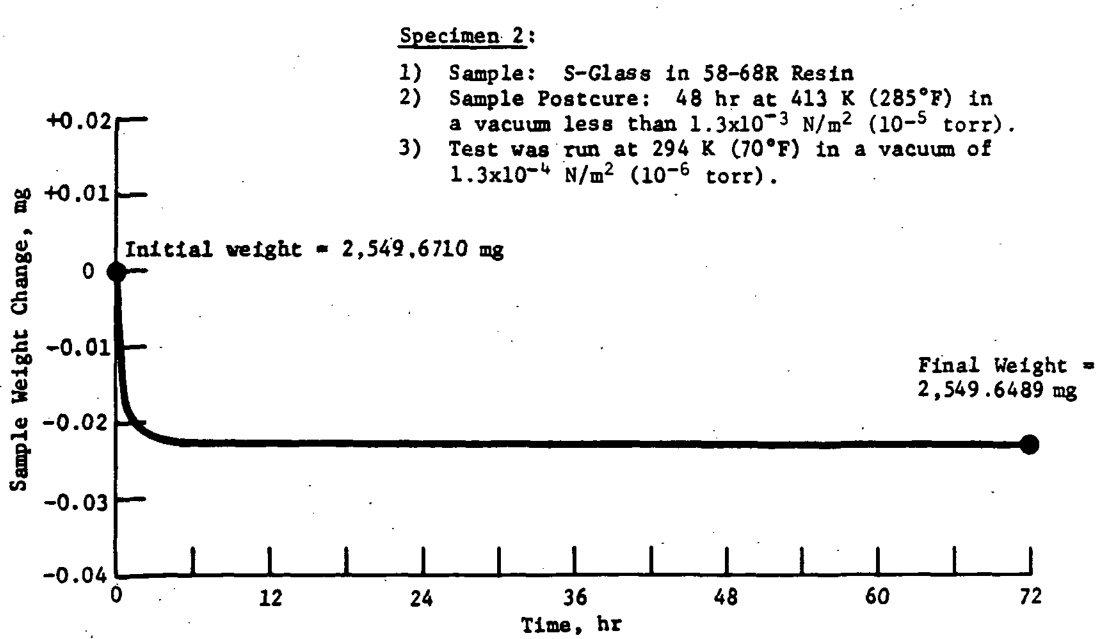


Figure 16.- Outgassing Test Results after Test Sample 2 Had Been Vacuum Postcured for 72 Hours

TEST ITEM DESIGN

Using the results of preliminary tests and the design information developed during concept design evaluation, six each 13 cm (5 in.) and six each 38 cm (15 in.) ID vacuum jacketed composite lines were designed depicting each of the selected concept configurations. The designs consisted of 63.5 cm (25 in.) long line sections with end fittings, vacuum instrumentation, and all necessary hardware. Additional design included thermal and strain instrumentation for use in the test program, and special overwrap and leak test tooling.

The vacuum jacketed composite line configurations, which were selected at the completion of these analyses, are representative of the liquid hydrogen feedlines required for Space Shuttle and Space Tug.

Physical Dimensions and Properties. - Physical dimensions and properties of the inner lines and the vacuum jackets for each of the selected design concepts are shown in Table XI.

Detailed engineering drawings were prepared for each design concept and copies of the drawings were included in the Second Quarterly Progress Narrative (ref. 3). The materials of construction and fabrication techniques are summarized in the fabrication section of this report.

Design Objective. - The design objective was to develop workable designs for each of the selected design concepts by applying technology from earlier composite feedline studies to vacuum jacketed composite feedlines. The design criteria, which were major considerations in the test item design, were defined in Table I.

End Fitting Design. - The criteria for end fitting design included:

1) capabilities of the various liner fabricators to weld thin foil to a relatively thick section of flange;

2) ease of assembly of the vacuum jackets over the inner lines;

3) thermal mass, stress concentration, and vacuum carry-through capability of vacuum jacket end fittings;

4) closure of the vacuum annulus;

5) ease of connecting composite tubes to other composite sections and to metallic end caps;

6) butt weld type fittings were selected for joining two sections of vacuum jacketed line to minimize weight and leakage.

TABLE XI.- TEST ITEM PHYSICAL DIMENSIONS AND PROPERTIES

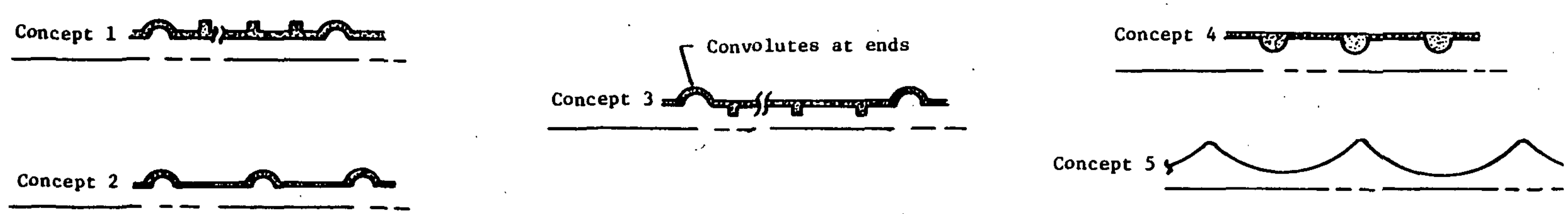
Test item configuration	Quantity	Diameter, cm (in.)	Length, cm (in.)	Material thickness, cm (in.)	Longitudinal weld		Convolutes		End fitting weld	Heat treat and age harden
					Qty	Type	Style	Qty		
Inner Line	3	13 (5)	63.5 (25.0)	0.008 (0.003)	1	Fusion	N/A		Fusion	Yes
Inner Line	3	13 (5)	63.5 (25.0)	0.013 (0.005)	1	Fusion	N/A		Fusion	Yes
Inner Line	6	38 (15)	63.5 (25.0)	0.013 (0.005)	1	Resistance	N/A		Resistance	Yes
Vacuum Jacket Concept 1	2	20 (8)	59.0 (23.25)	0.015 (0.006)	2	Fusion	External	2	Fusion	No
Vacuum Jacket Concept 3	2	46 (18)	59.0 (23.25)	0.015 (0.006)	3	Fusion	External	2	Fusion	No
Vacuum Jacket Concept 2	2	20 (8)	59.0 (23.25)	0.015 (0.006)	2	Fusion	External	14	Fusion	No
Vacuum Jacket Concept 2	2	46 (18)	59.0 (23.25)	0.015 (0.006)	3	Fusion	External	22	Fusion	No
Vacuum Jacket Concept 4	2	20 (8)	59.0 (23.25)	0.015 (0.006)	2	Fusion	Internal	15	Fusion	No
Vacuum Jacket Concept 5	2	46 (18)	59.0 (23.25)	0.019 (0.0075*)	1	Fusion	Tension Membrane	3	N/A	No

Except as noted all materials are Inconel 718

*Material of the tension membrane vacuum jacket was 321 stainless steel chem-milled to the average wall thickness.

Where required end fittings were made of 304 stainless steel

Vacuum Jacket Concepts



Note: Concept details are further defined in Figures 3 thru 7

The thickness of the main body of the end fitting is controlled by three factors: (1) minimum thickness to withstand internal pressure (inner line) and external pressure (vacuum jacket); maximum thickness permitted by the welding process that is generally three times the liner thickness; and (3) the required thickness to join the tube to an adjacent component. Diagrams of the end fittings designed for the various test items are shown in Figure 17.

The end fitting selected for the 38 cm (15 in.) diameter inner lines was designed for a resistance welded liner-to-end-fitting-joint. The end fitting selected for the 13 cm (5 in.) diameter inner lines is similar to the large fitting except for the weld prep area which is shaped to provide an approximately equal area for effective weld heat buildup during welding. This style of end fitting is designed for a fusion weld liner-to-end-fitting-joint. The end fittings selected for the 46 and 20 cm (18 and 8 in.) vacuum jackets, were designed to be fusion-welded to the thin vacuum jacket liner and heliarc-TIG welded to the thick portion of the inner line end fittings. Figure 18 shows typical installation of the vacuum jacket end fitting over the inner line end fitting. Figure 19 shows typical installation of the tension membrane end fitting over the inner line end fitting.

Inner Line Design. - The inner line design analyses (liner heat treat versus annealed, bonding, torsion loading, and tension loading are included in Appendix A. The final conclusion after considering analyses results, and the $S = \frac{Pr}{t}$ relationship, was that liner material thickness is determined by minimum gage manufactuing and handling limitations. A design objective was to not exceed the yield stress of the liner material at the line working pressure. This was easily achieved by 0.008 and 0.013 cm (0.003 and 0.005 in.) heat treated Inconel 718 with a yield strength of 114,000 N/cm^2 (165,000 psi). The hoop stresses, at working pressure are 34,500 N/cm^2 (50,000 psi) and 103,000 N/cm^2 (150,000 psi) for the 13 cm (5 in.) and 38 cm (15 in.) diameter lines, respectively.

This design approach results in the overwrap providing additional design margin and handling capability. It is significant that the overwrap is not required for pressure loading.

Vacuum Jacket Design. - The structural design analyses of the vacuum jackets for radial and axial external pressure loading, performed during concept evaluation, determined the liner and overwrap thickness, convolute size and spacing, standoff support configuration and spacing, and the tension membrane configurations.

Test Item Assembly Design. - To facilitate testing and to test a typical joint configuration, the vacuum jacketed composite line test configuration consisted of two like design concepts butt-welded together as shown in Figure 20. Heavy weight tube caps were used for interfacing with the test facility. Thermocouples and strain gages were designed for installation as shown by Figure 20, and are indicated by T1, T2 . . . and S1, S2, . . ., respectively. The instrumentation wiring was fed through the vacuum end closure via vacuum connectors. The vacuum annulus of each tube was manifolded together with 1.27 cm (0.50 in.) diameter tubing to a VEECO vacuum isolation valve. A cold cathode ionization gage was provided in the manifold for monitoring vacuum in the range of 10^{-1} to 10^{-4} N/cm^2 (10^{-3} to 10^{-6} torr).

Tooling. - Concurrent with the test item design a mechanical fixture to serve as a leak check tool, proof pressure tool, and overwrap tool was also designed. Figure 21 shows the basic design concept of the tool. Separate fixtures were designed for each different diameter tube and vacuum jacket. A heavy weight inner line was used for structural integrity and leak checks on the tension membrane jacket.

Vacuum Jacket Design Modification. - Upon initial pump-down of the vacuum jacket annulus, a collapse of the vacuum jacket was experienced due to external pressure. Failure analysis (Appendix - D) revealed that the bond of the glass-fiber overwrap to the metal liner had failed, thus exposing the liner to total external pressure loading. Investigation and testing performed during the failure analysis showed that the bond line was loaded in peel instead of pure tension. The bonding strength in peel was poor, even on specially prepared test samples. It was further found that when the composite structure was loaded, but in a manner so as not to load the bond line, the structure developed anticipated strength.

As a result of this failure and subsequent analysis, it was concluded that the concept of using a very thin metallic liner bonded to a glass-fiber overwrap was not workable with the surface preparation and bonding techniques used. While others have had success in making bonds with good peel strength using different resin systems and surface roughing techniques, it was apparent that bonding development beyond the scope of this contract would be required to obtain an acceptable process. This conclusion led to the development of an evacuated bag, which was placed over the composite vacuum jackets during testing, and to the redesign of the vacuum jacket liners.

A typical evacuated bag installation on the composite vacuum jackets is shown by Figure 22. The effect of the evacuated bag was to transfer the external pressure loading to the outside of the composite structure and thus eliminate the loading on the bond. This configuration proved successful and was used on the remaining composite vacuum jackets throughout the test program.

The vacuum jacket redesign consisted of increasing the liner wall thickness, as required, to withstand external pressure loading without a requirement to bond the liner to the overwrap. The overwrap is still applied to provide liner protection in handling and additional structural margin. Calculated metal liner thicknesses required for the composite vacuum jacket design are provided in Table XII.

TABLE XII. REQUIRED VACUUM JACKET LINER THICKNESS TO WITHSTAND 25 N/cm^2 (36.7 psi) EXTERNAL PRESSURE VERSUS LINER DIAMETER

Vacuum jacket diameter (OD) cm (in.)	Liner gage cm (in.)
13 (5)	0.025 (0.010)
20 (8)	0.030 (0.012)
33 (13)	0.035 (0.014)
46 (18)	0.041 (0.016)
58 (23)	0.046 (0.018)

Without overwrap, the metal liner thickness required for external pressure does not provide adequate resistance to damage for handling during installation or maintenance. Since the overwrap is of very low density, the overwrapped line is of lighter weight than the conventional all-metal vacuum jacketed line which would require a thicker metal gage.

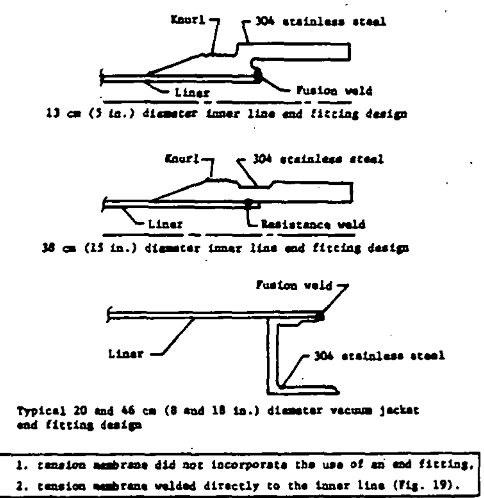


Figure 17. Inner Line and Vacuum Jacket End Fitting Configuration

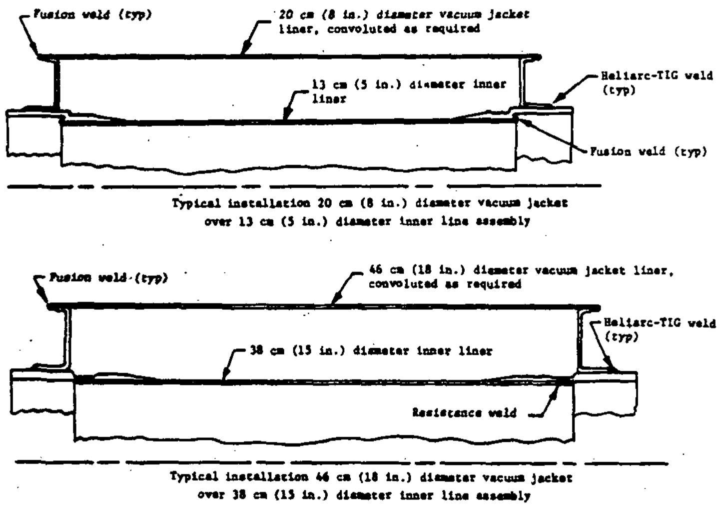


Figure 18. - Vacuum Jacket Installation Over Inner Line

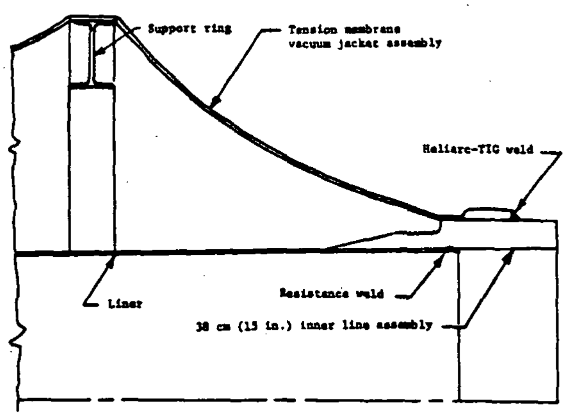


Figure 19. - Tension Membrane Installation Over Inner Line

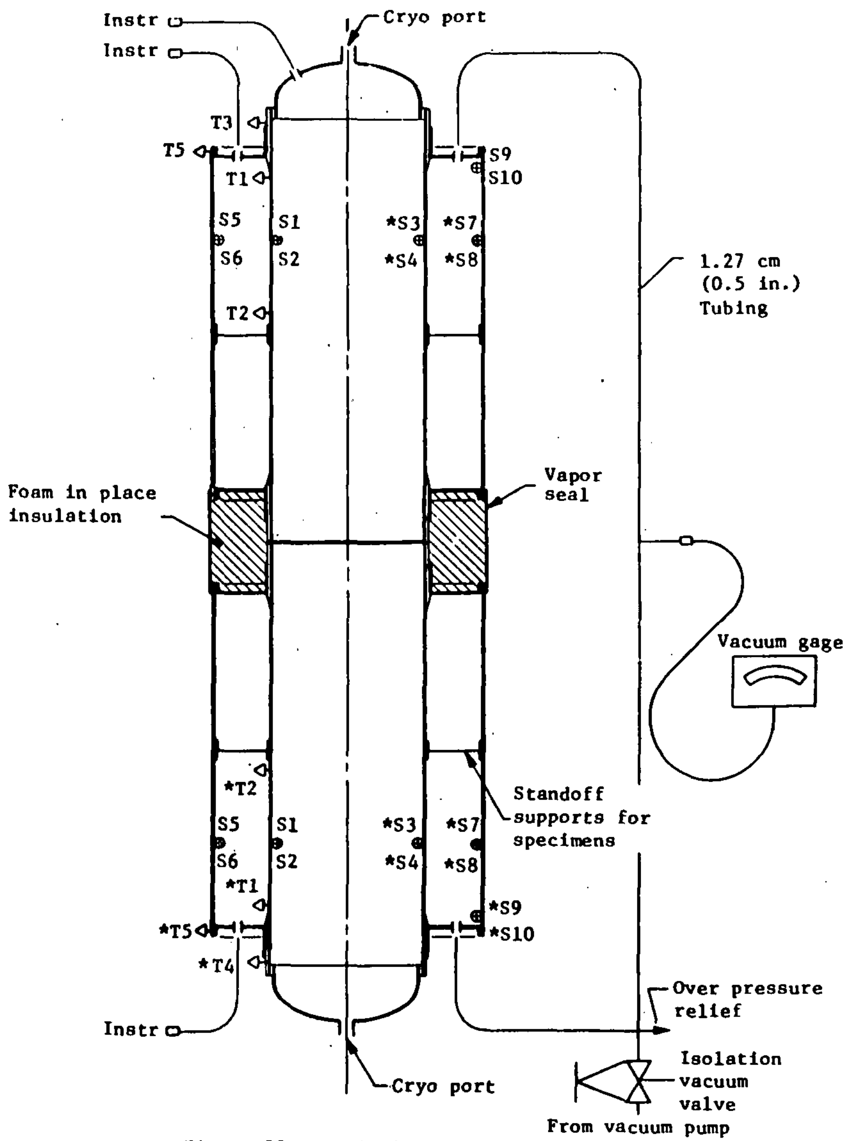


Figure 20.- Typical Test Item Assembly Configuration and Instrumentation

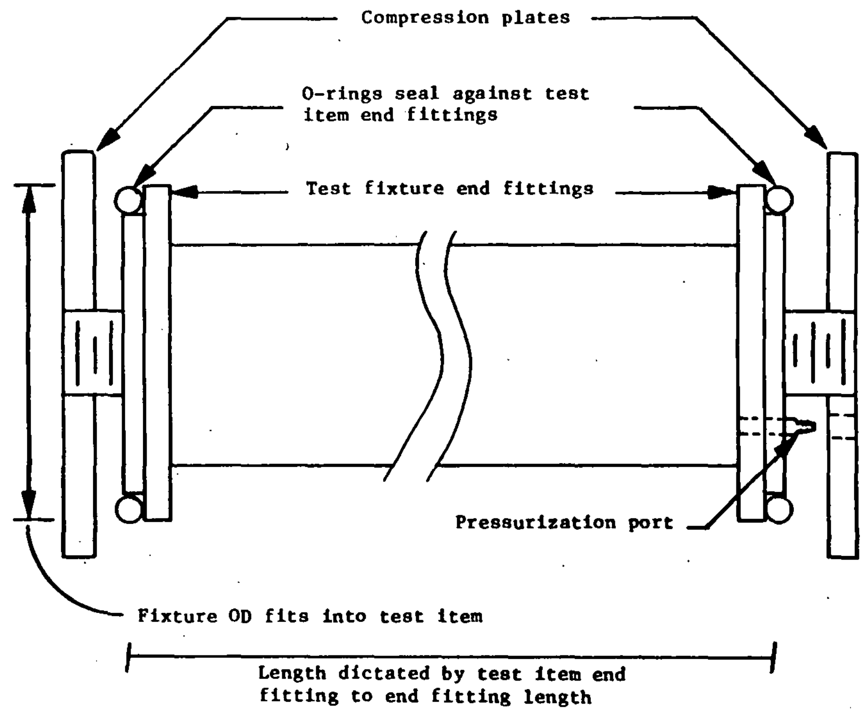


Figure 21.- Leak Check, Proof Pressure and Overwrap Tool

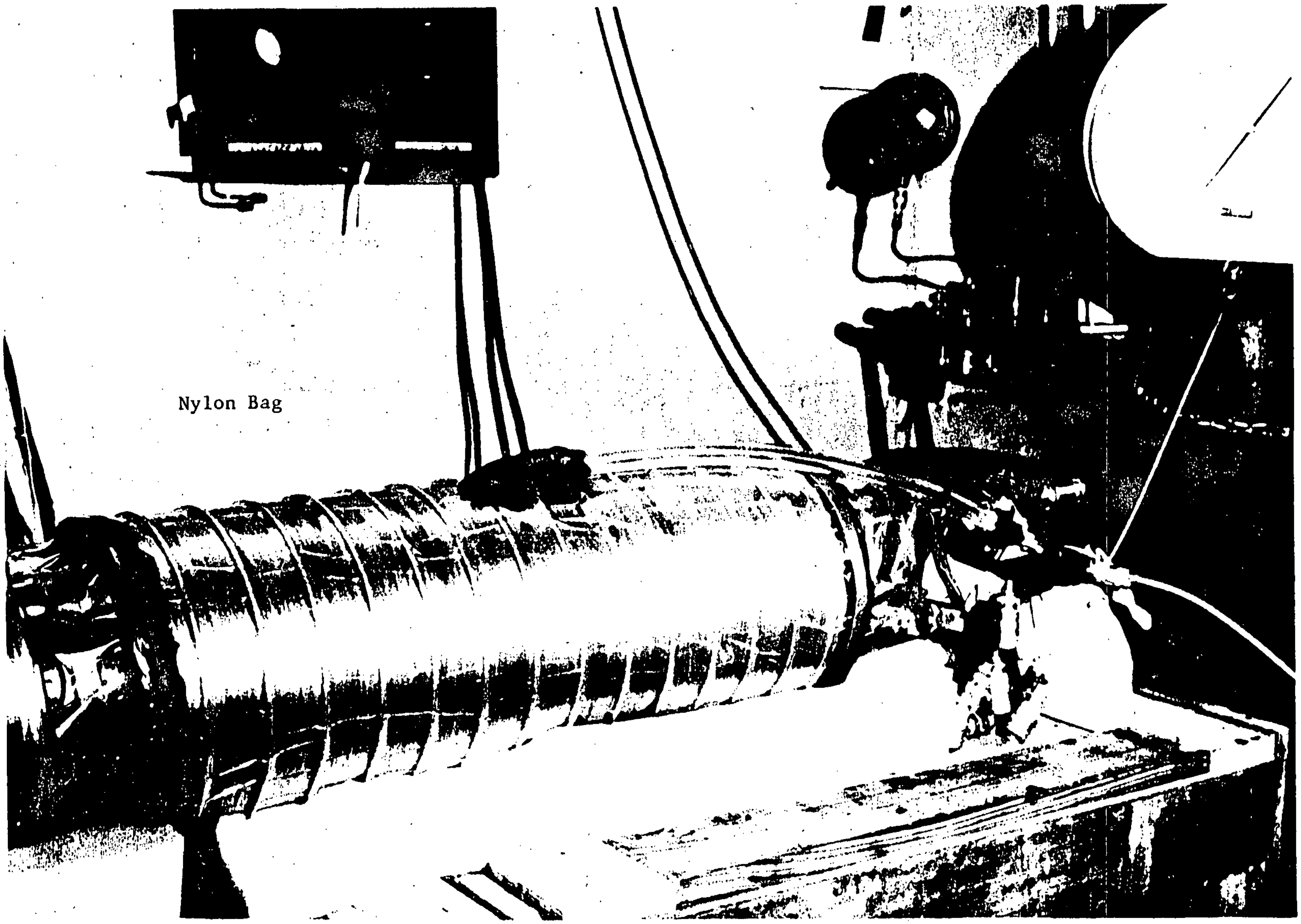


Figure 22. - Nylon Bag Assembly on Vacuum Jacketed Line

FABRICATION

The fabrication effort consisted of the following major functions:

1) evaluating and selecting vendors;

2) fabricating liners;

3) fabricating end fittings;

4) joining liners and end fittings;

5) overwrapping and curing the assembly (except tension membrane vacuum jacket);

6) mounting instrumentation;

7) joining inner liners and vacuum jackets; and

8) performing various in-process leak checks.

The materials, manufacturing and welding techniques, along with fitting fabrication and fitting attachment processes used to produce the test item inner liner, were similar to those developed on earlier programs. New techniques, however, were required to fabricate vacuum jacket liners and to overwrap internal and external convolutes. The quantities fabricated were:

six-13 cm (5 in.) diameter inner lines

six-38 cm (15 in.) diameter inner lines

six-20 cm (8 in.) diameter vacuum jackets

six-46 cm (18 in.) diameter vacuum jackets (includes 2 tension membrane vacuum jackets).

The general fabrication sequence for the test items is depicted by the flow charts shown in Figures 23 through 26.

End Fitting Fabrication.- The requirements of the program dictated that butt-weld style, flight-weight fittings be used on the test specimens. The weld prep configurations of the end fittings, where the liner is joined to the end fitting, were developed by the liner fabricators.

To facilitate assembly of the vacuum jacket over the inner line, the end fittings of the vacuum jacket were dimensionally controlled to provide a minimum clearance fit over the inner line end fittings. One end fitting was machined to a smaller outside

diameter than the other to facilitate assembly. All composite line end fittings were made of 304 stainless steel. The 13 cm (5 in.) inner line end fittings were machined from sections of pipe. The 38 cm (15 in.) inner line end fittings were machined from rings that were rolled from flat stock and seam welded. The vacuum jacket end fittings were machined from a solid plate.

Liner Fabrication and Joining End Fittings.- The three different methods of liner fabrication that were used include resistance welded, fusion welded from stock of desired final thickness, and, for the tension membrane, fusion welded from thick stock and chem-milled to desired final thickness. The type of weld used to form the liner was also used to attach the end fitting (either resistance or fusion welding).

Resistance welding technique: Resistance welding the inner liner (Fig. 27) required the liner to be roll formed to the desired diameter with a slight overlap and mating surface. An anode was placed in the liner and a resistance weld run down the length of tube. The excess overlap on both the inside and outside of the tube was then peeled away from the weld. After peeling the end fittings were installed on the liner using the same welding technique. A major advantage of this weld method is that heat treating and age hardening can be performed before resistance welding, and the low heat and small heat-affected-zone do not degrade the heat treat.

The 38 cm (15 in.) inner lines were all fabricated by resistance welding, one of which is shown in Figure 28.

Fusion welding technique: The liner was formed by rolling a tube of the final thickness material (Inconel 718) to the proper diameter and preparing each of the butting edges with a slight curl. The seam along the length of the liner was then fusion welded polished and planished, thus making the weld area conform to overall tube size with no weld buildup inside or outside the tube. Next, inner line liners were heat treated and age hardened, followed by fusion welding of the end fittings. The vacuum jackets were fusion welded but not heat treated; convolutes were formed and end fittings were fusion welded to each end.

This fusion welding process was used for the 13 cm (5 in.) diameter inner lines and all of the vacuum jackets except the tension membrane. Figures 29 through 33 show a typical assembly of each design concept.

Fusion welding from thick stock and chem-milling to the desired final thickness: The liner was formed by rolling a tube from 0.046 cm (0.018 in.) thick stock (321 stainless steel) to 38.4 (15.1) diameter and preparing each of the butting edges with a slight curl. The seam along the length of the liner was then fusion welded, polished and planished thus making the weld area

conform to overall tube size with no weld buildup inside or outside the tube. The liner was then pressure formed into the tension membrane configuration and chem-milled to the desired thickness [0.018 cm (0.007 in.) through 0.025 (0.010 in.) thick sections]. This technique of liner fabrication was used only on the tension membrane concept. Figure 34 shows the completed tension membrane vacuum jacket.

Convolute formation: Before installing end fittings on the composite vacuum jacket liners, convolutes were roll formed into the vacuum jackets. Two types of convolutes were used; internal and external. The convolutes served to increase the structural capability of the vacuum jacket and/or provide an expansion/contraction capability.

The external convolutes were formed one convolute at a time. An internal, six piece, mechanical, expanding, pie die was used in conjunction with finishing rollers to form the convolute (Fig. 35). Starting with an annealed liner, a properly sized pie die was installed inside the liner and expanded to one-quarter the desired convolute height. The pie die was then contracted and rotated 0.5 rad (30 deg). It was again expanded, this time to one-half the desired convolute height. This procedure was repeated at three-quarters the desired convolute height and at the final desired convolute height. Rotating the pie die served to reduce the flat areas developed at the split portions of the die. However, since the rotating procedure did not completely eliminate the flat spots, it was necessary to use finishing rollers to finish the convolute. A roller machined to the convolute shape was set inside the liner in the convolute. Two rollers straddled the convolute on the outside of the liner. Simultaneously, all rollers then traveled around the convolute smoothing the flat areas. The convolute was then complete. The process was repeated for each convolute. The liners did not require any additional annealing during the various formation heights of the convolutes.

The internal convolutes were formed, one convolute at a time. An internal mandrel with the proper number and shape of convolutes was used with an external roller to form the convolutes (Fig. 36). Starting with an annealed liner, the mandrel was installed inside the liner. A regulated constant force was applied to the external roller forming the convolute to one-quarter its desired depth. The liner was allowed to float on the internal mandrel and the roller was rotated forming the convolute. After one revolution, the force on the roller was increased, another revolution was made and the convolute was at one-half the desired depth. A total of 4 revolutions are required to reach the desired convolute depth. The process was repeated for the desired number of convolutes. The convolutes achieved by this process are smooth and do not require additional finishing. The liners do not require additional annealing during the various formation depths of the convolutes. Internal convolutes were used on two of the 20 cm (8 in.) diameter vacuum jackets.

The tension membrane shown in Figure 37 is formed using an entirely different process. After fusion welding, the liner is annealed and is installed in a hydrostatic bulging die. The liner is prebulged, annealed, and then final-formed. After forming, the liners are chem-milled to the final jacket thickness.

The tension membrane requires support rings (Fig. 38) for structural integrity. After installing support rings, strain gages, vacuum valve, vacuum sensor, and instrumentation feedthroughs, the tension membrane was welded to a composite inner line resulting in the completed assembly shown in Figure 39.

Two tension membrane assemblies were fabricated. Additional fabrication details are provided in Appendix E.

Overwrap Application. - After inner line and vacuum jacket liner assemblies were complete, they were prepared for overwrap. All liners were overwrapped except the tension membrane vacuum jackets. Just before overwrap, the liners were cleaned to prepare the liner surfaces for bonding the glass/resin matrix to the liners. The cleaning procedure used was as follows:

1) the liner was degreased with methyl-ethyl-ketone and toluene;

2) the liner was thoroughly washed with an alkaline detergent at 311 to 344 K (100 to 160°F) consisting of the following:

	parts/weight
Sodium metasilicate	3.0
Tetrasodium pyrophosphate	1.5
Sodium hydroxide	1.5
Nacconal NR (Allied Chemical Company)	0.5
Distilled water	134.0

3) rinsed thoroughly with cold, running tap water, followed by distilled water;

4) air dried at ambient temperature as observed by visual inspection;

5) brushed over area to be bonded with Pasa-Jell 105, let set for 30 minutes, and rinsed thoroughly with tap water;

6) applied the overwrap within two hours after rinsing off the Pasa-Jell 105.

The overwrap on the inner lines consisted of three distinct layers: hoop, longitudinal strips of cloth, and hoop, applied in that order. The hoop roving was applied under 1.4 kg (3 lb) wrap tension. The longitudinal cloth was laid the length of the liner, and consisted of equal widths of cloth separated by equal width gaps. The hoop wound glass-fiber roving was 20 end S/HTS-901 fibers preimpregnated with 58-68R resin. The longitudinally laid cloth was 1557 glass, hand-impregnated with 58-68R resin. The resin content was 20 to 25%. The hoop wound roving was applied at a rate of 6.3 turns/cm (16 turns/in.). Required instrumentation was installed on the longitudinal cloth and secured in place when the final hoop layer of overwrap was applied. Table XIII shows specific details of the overwrap of the inner lines. The 58-68R resin matrix and cloth mat require a cure cycle at elevated temperatures. The composite cure cycle used on the inner lines is depicted in Figure 40. Constant positive internal pressure was maintained during overwrap and cure. In addition to the overwrap already defined, four of the 38 cm (15 in.) inner lines required additional overwrap. A center support pad consisting of 12 layers of cloth 2.0 cm (0.8 in.) wide was applied around the circumference of the tube. The resin matrix and cure cycle were identical to that used on the inner line with positive pressure maintained in the line during cure.

TABLE XIII.- INNER LINE TEST ITEM OVERWRAP PARAMETERS

Test item	Quantity	Liner Internal Pressure N/cm^2 (psi)	Overwrap tension per 20 ends kg (lb)	Longitudinal cloth width and gap cm (in.)
13 cm (5 in.) Diameter Inner Line	6	13.8 (20)	1.4 (3.0)	2.2 (0.87)
38 cm (15 in.) Diameter Inner Line	6	10.3 (15)	1.4 (3.0)	2.2 (0.87)

The overwrap on the vacuum jackets consisted of two layers applied at a (+) and (-) 0.09 rad (5 deg) angle, criss-cross pattern. The glass-fiber roving was 20 end S/HTS-901 fibers preimpregnated with Epon 828-mpda resin. The resin content was 32 to 38%

Required instrumentation was installed under the last layer of overwrap. Table XIV shows specific details of the overwrap of the vacuum jackets. The Epon 828-mpda resin matrix requires a cure cycle at elevated temperatures. Several combinations of time and temperature are acceptable. Figure 41 shows the cure temperature profile used for the vacuum jackets. Positive internal pressure was maintained during overwrap and cure. In addition to the overwrap already defined, two of the 20 cm (8 in.) vacuum jackets required additional overwrap. Concept 1 required additional hoop rings around the circumference of the tube. The layers of hoop roving were applied over a 0.3 cm (0.125 in.) width 14 equal spaces along the vacuum jacket. The wrap tension, roving, resin matrix, and cure cycle were identical to that used on the jacket.

Positive pressure was again maintained during overwrap and cure. Figure 42 shows an overwrapped inner liner with a center support pad.

Hoop support rings: The hoop support rings used in Concept 3 were fabricated by wrapping 12 layers of hoop roving to a width of 0.19 cm (0.075 in.) on a mandrel 46 cm (18 in.) in diameter, and curing the resin matrix. The hoop rings were then cut from the mandrel and splice taken out. When installed in side the vacuum jackets (Fig. 46), the rings exert a small radial force on the liner. With the ends butted together, the ring will take compressive loads. Forty-four of the support rings were required.

TABLE XIV.- VACUUM JACKET TEST ITEM OVERWRAP PARAMETERS

Test Item	Quantity	Liner internal pressure N/cm^2 (psi)	Overwrap tension per 20 ends kg (lb)	Wrap angle (+) (-) per 2 layers rad (deg)
20 cm (8 in.) diameter vacuum jacket	6	12.4 (18)	1.4 (3)	0.09 (5)
46 cm (18 in.) diameter vacuum jacket	4	6.2 (9)	1.4 (3)	0.09 (5)

The wrap tension, roving, resin matrix, and cure cycle were identical to that used on the inner lines.

Composite structural supports: All of the 46 cm (18 in.) vacuum jackets required internal standoff supports.

The standoffs were fabricated by laying cloth and roving over a matched metal tool, formed to a 2.1 rad (120 deg) segment of a circular I-beam (Fig. 47). The cloth used in the layup was 181, while 20 end S/HTS-901 was used as the roving. The 58-68R resin matrix was used with an elevated temperature cure. The matched tool was clamped to provide restraint to the composite during the cure cycle. Twelve composite I-beams were constructed for use in the four 46 cm (18 in.) vacuum jackets. Three of the I-beams were installed in each jacket forming one continuous I-beam around the circumference. The I-beam was joined with aluminum splice tabs and #10 screws. When the vacuum jacket assembly is installed properly over the inner line, the I-beam will rest over the inner pad forming a structural tie between the vacuum jacket and the inner line, normally called the standoff. In a total vacuum condition, i.e., in space, there will be a thermally efficient gap between the standoff and the inner line.

<u>In-Process Leak Checks</u>.- Two types of in-process leak checks were performed on the test items. These were helium mass spectrometer and dye penetrant leak checks. Dye penetrant leak checks were made on the liner and end fitting welds. Low pressure helium mass spectrometer leak checks were performed on the completed liner assemblies by the liner fabricators. Safety restrictions and/or material yield strength precluded leak checks at operating pressure until the overwrap system was installed and cured. Upon receipt of the test items from the vendors, another low pressure helium leak check was performed to determine if any damage occurred during shipping. The final in-process leak check at operating pressure was performed after the assembly had been overwrapped and cured. The results of the leak checks are covered in the Testing section.

<u>Insulation Installation</u>.- To improve the emissivity characteristics of the composite inner lines, one layer of double aluminized ½-mil mylar was installed over the composite. Figure 48 shows a typical installation of the aluminized mylar.

Required Modification and Fabrication Problems.- During fabrication of the various test items, the following problems which required some modification of the design criteria were encountered:

Inner line liners [13 cm (5 in.)]: The system operating pressure of 41 N/cm^2 (60 psi) absolute, dictated that the lines could be fabricated at the previously established minimum gage for composite lines, which was 0.008 cm (0.003 in.). Upon receipt of the 13 cm (5 in.) diameter inner lines from the fabricators, the helium mass spectrometer leak check revealed unacceptable leakage rates in all six of the inner line assemblies. The inner lines were returned to the fabricator where an attempt was made to salvage the lines by repairing the leaking welds. Three of the lines were salvaged. Before proceeding with refabrication of the other three, the vendor required an increase in the tube thickness from 0.008 to 0.013 cm (0.003 to 0.005 in.) for the following reasons:

1) Welded part rejection rate was approximately 10 to 1 for the 0.008 cm (0.003 in.) thickness.

2) Leakage through the grain structure in the 0.008 cm (0.003 in.) thickness is not uncommon; therefore, in some instances, leakage cannot be prevented, driving part rejection rates even higher.

3) With the high rejection rate and relatively high cost of the welding process and materials, this thickness would probably be cost-prohibitive for any production contract.

Vacuum jacket liner welding: The original design of the vacuum jacket liners called for fabrication using 304 stainless steel. Complications developed in attempting to weld the material. The vendor's particular mill run of 304 stainless steel stock proved to be porous and not of the highest purity required to achieve good welds for this thickness of material. The alternative suggested by the fabricator was to switch to Inconel 718. The change was approved.

Assembly welding: During the welding of an externally convoluted 20 cm (8 in.) vacuum jacket to a 13 cm (5 in.) inner line a hole was burned through the glass overwrap and the liner of the vacuum jacket. This was caused by an improper grounding technique during the welding operation. A standard grounding procedure was developed as a result of this incident, and was used successfully for the remaining welding.

With the use of a cryogenic, vacuum compatible adhesive, an attempt was made to repair the burned hole in the liner. A subsequent failure (implosion) of the liner during initial vacuum pull-down, did not allow an evaluation of the success of the repair. It was noted, however, after the vacuum jacket imploded, that the adhesive still filled the burned hole. A complete discussion of this failure is provided in Appendix D.

Test Item Assembly.- After overwrap, installation of the composite I-beams, support rings and insulation, the inner lines and vacuum jackets were prepared to be joined into assemblies. Holes were drilled in the vacuum jacket end fittings to install instrumentation feedthroughs and vacuum access ports. A 1.27 cm (0.5 in.) stainless steel tube was used for the vacuum port and a 0.95 cm (0.375 in.) stainless steel tube was selected for the instrumentation feedthrough. After welding these in place, the vacuum jackets were mated with the inner lines and welded. End caps to interface with the test facility were welded into each end of the test specimen as shown in Figure 49. The vacuum annulus of each tube was manifolded together with 1.27 cm (0.5 in.) tubing that contained a vacuum isolation valve, a connector for vacuum readout, and a burst disk. The assembly was completed by adding foam insulation over the weld joining the two lines, and over the tube caps at each end.

Test Fixture Design and Fabrication.- Test fixtures were either modified from those used in Contracts NAS3-12047 and NAS3-14370 (ref 1 and 2) or specifically designed for this program. A test fixture was designed and fabricated for use on the thermal, pressure cycle tests, pressure surge tests, and acoustics tests. The thermal, pressure cycle test fixture consisted of a liquid hydrogen supply, liquid nitrogen supply, hot gas supply, and structural support. The pressure surge test fixture consisted of a liquid nitrogen supply and structural support. The acoustic test fixture consisted of a liquid nitrogen supply, structural support and acoustic source. Details and schematics of these fixtures are shown in the Test section.

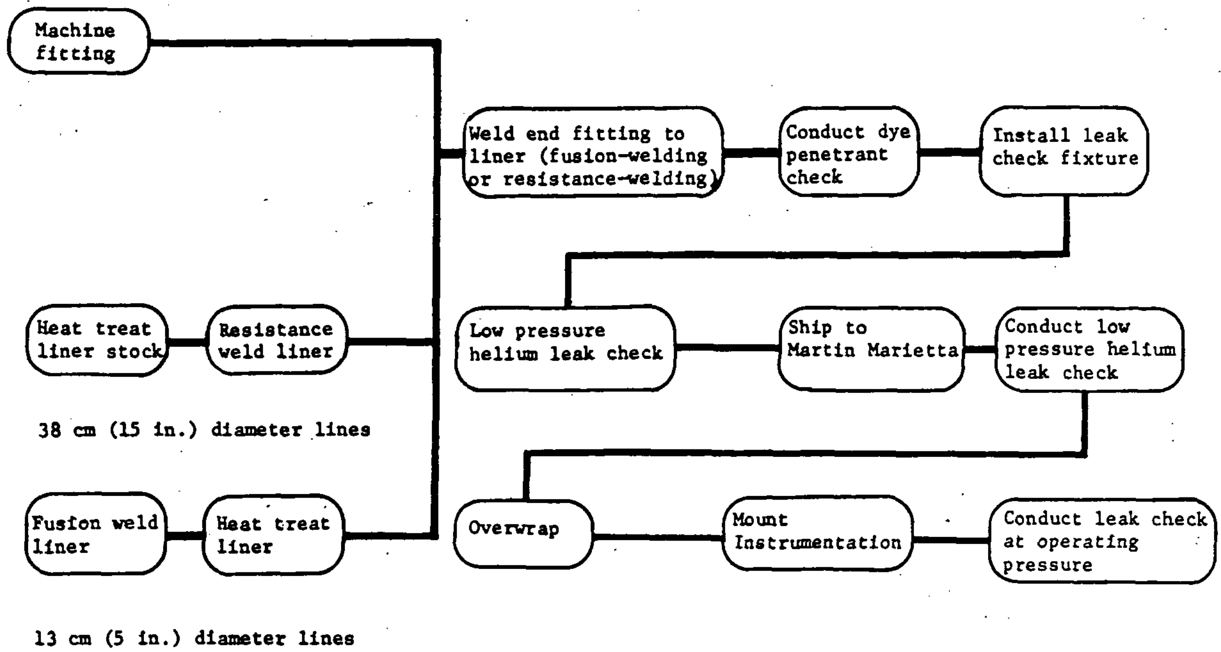


Figure 23.- Generalized Fabrication Flow Chart for the Inner Lines

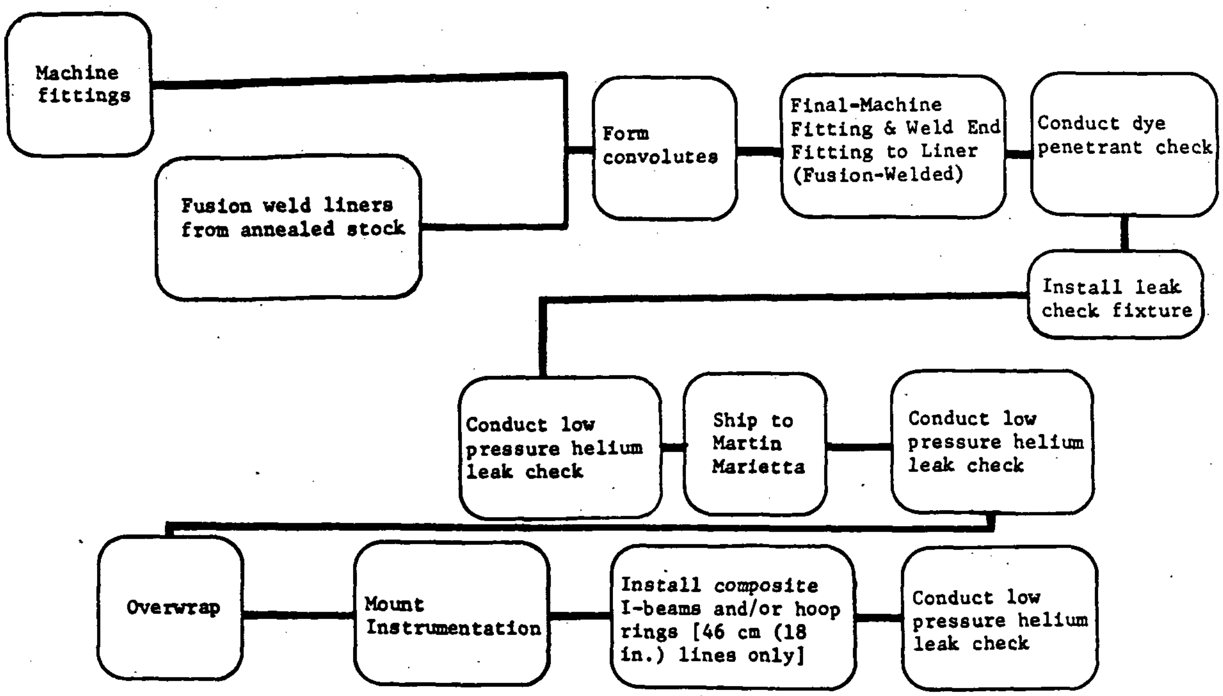


Figure 24.- Generalized Fabrication Flow Chart for the Vacuum Jackets (Excluding Tension Membrane Vacuum Jackets)

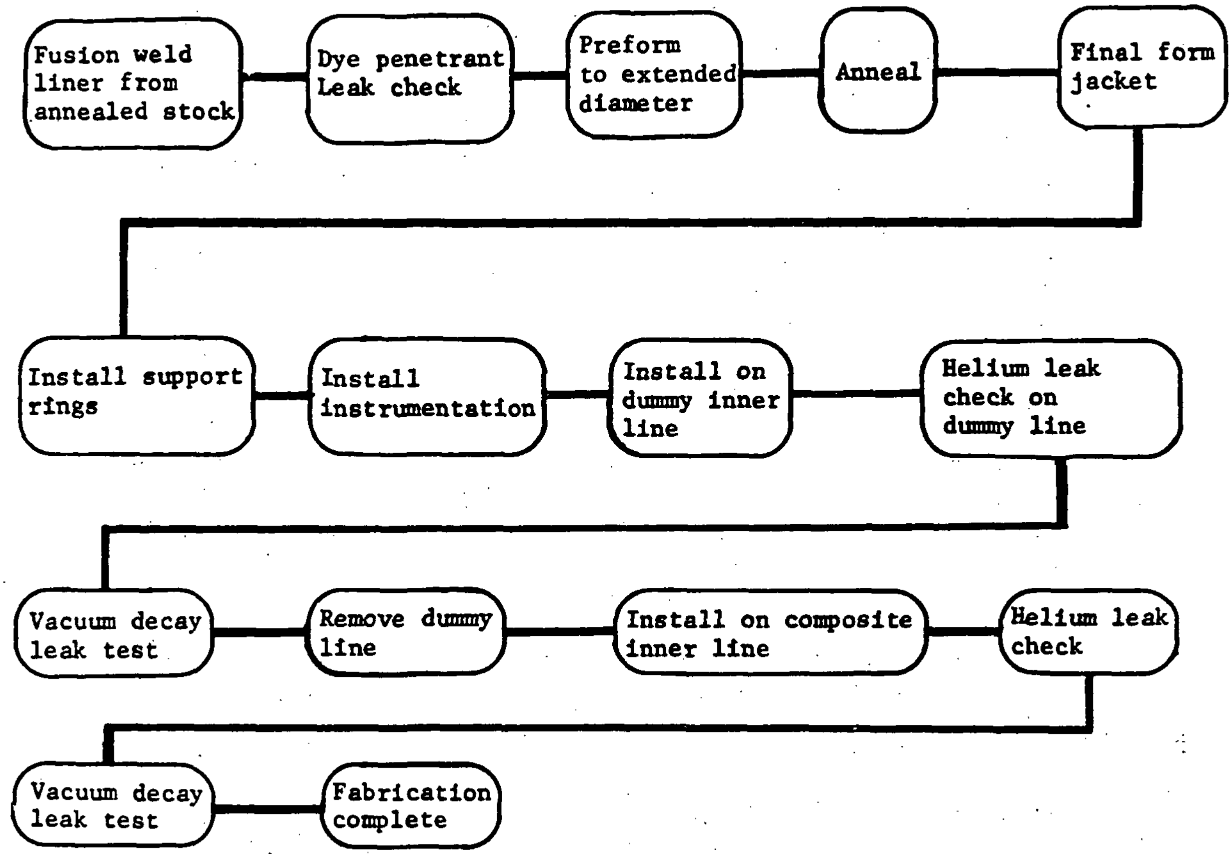


Figure 25.- Generalized Fabrication Flow Chart for the Tension Membrane Vacuum Jacket

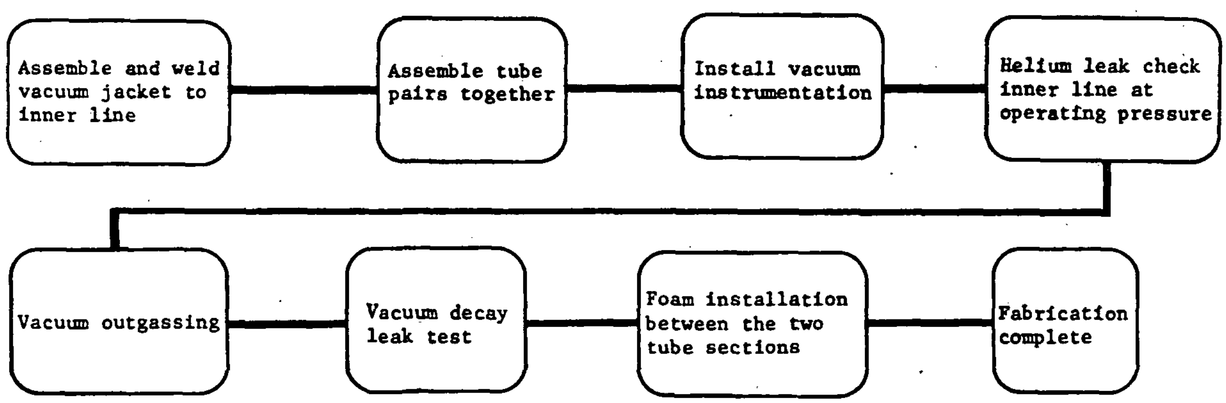


Figure 26.- Generalized Fabrication Flow Chart for the Assembly of the Inner Lines and the Vacuum Jackets

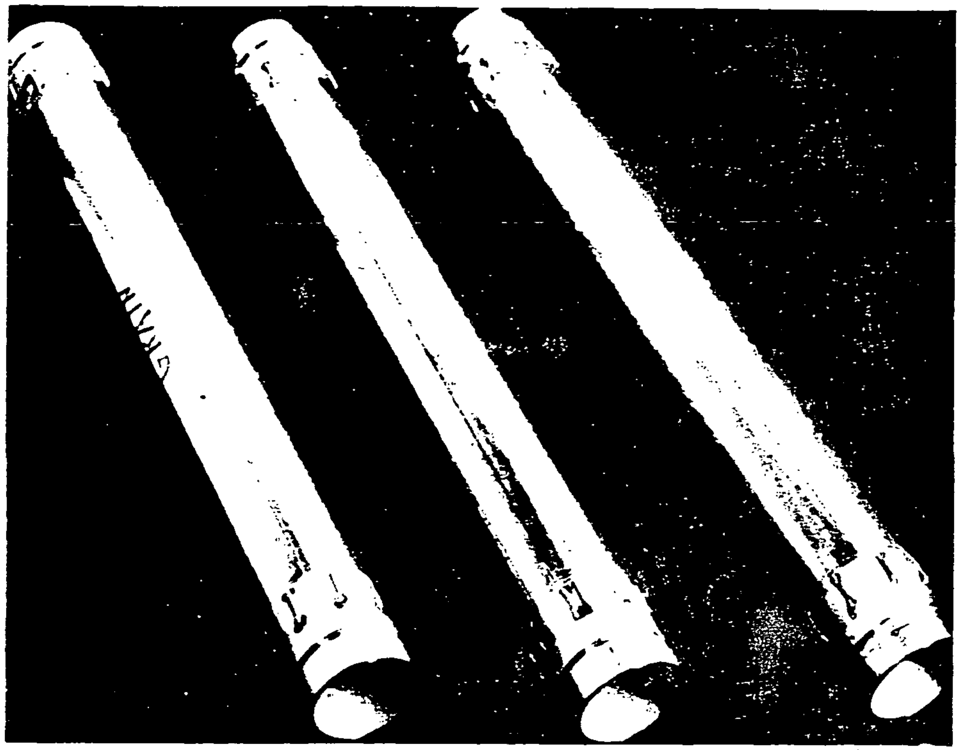


Figure 27.- Peeled and Unpeeled Resistance Welded Liners, 5 cm (2 in.) Diameter

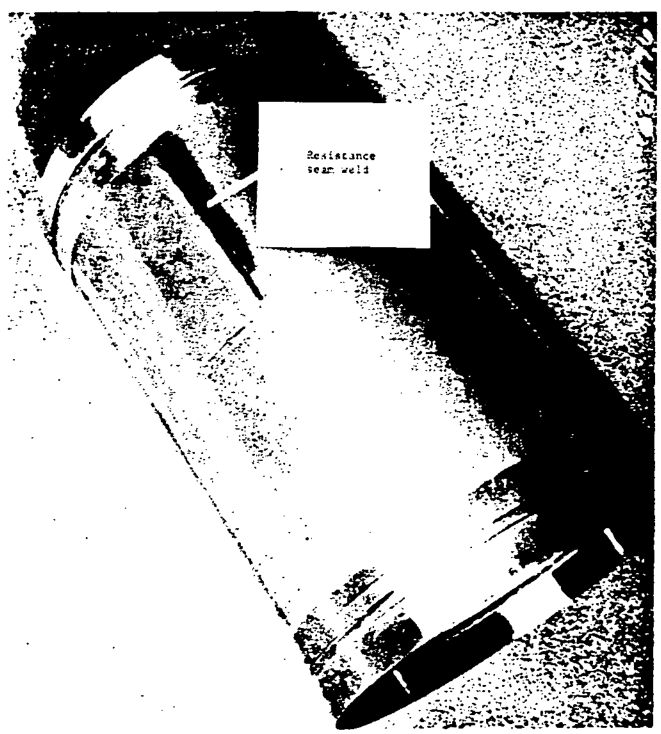


Figure 28.- Resistance Welded Inner Line Liner, 38 cm (15 in.) Inconel 718

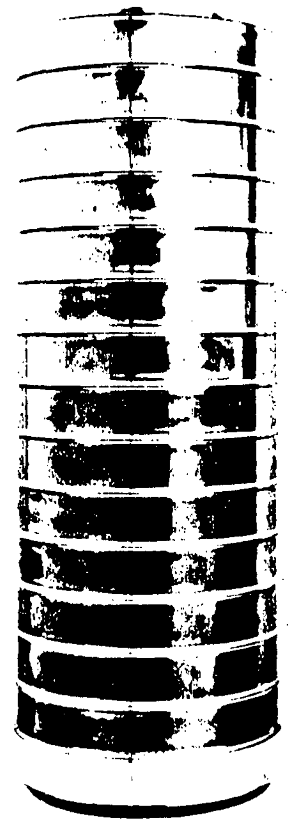


Figure 29. - Fusion Welded Vacuum Jacket Liner, 20 cm (8 in.) Diameter, Inconel 718, External Convolutes (Concept 2)

Figure 30. - Fusion Welded Vacuum Jacket Liner, 20 cm (8 in.) Diameter, Inconel 718, Smooth Liner To Be used with External Glass Ribs (Concept 1)

Figure 31. - Fusion Welded Vacuum Jacket Liner, 20 cm (8 in.) Diameter, Inconel 718, Internal Convolutes (Concept 4)

Figure 32. - Fusion Welded Vacuum Jacket Liner, 46 cm (18 in.) Diameter, Inconel 718, Smooth Liner To Be Used with Internal Hoop Supports (Concept 3)

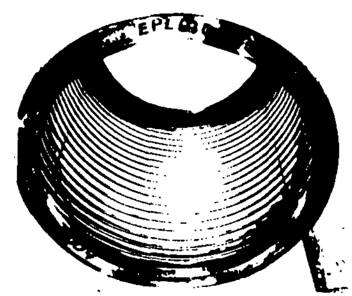


Figure 33. - Fusion Welded Vacuum Jacket Liner, 46 cm (18 in.) Diameter, Inconel 718, External Convolutes (Concept 2)

FOLDOUT

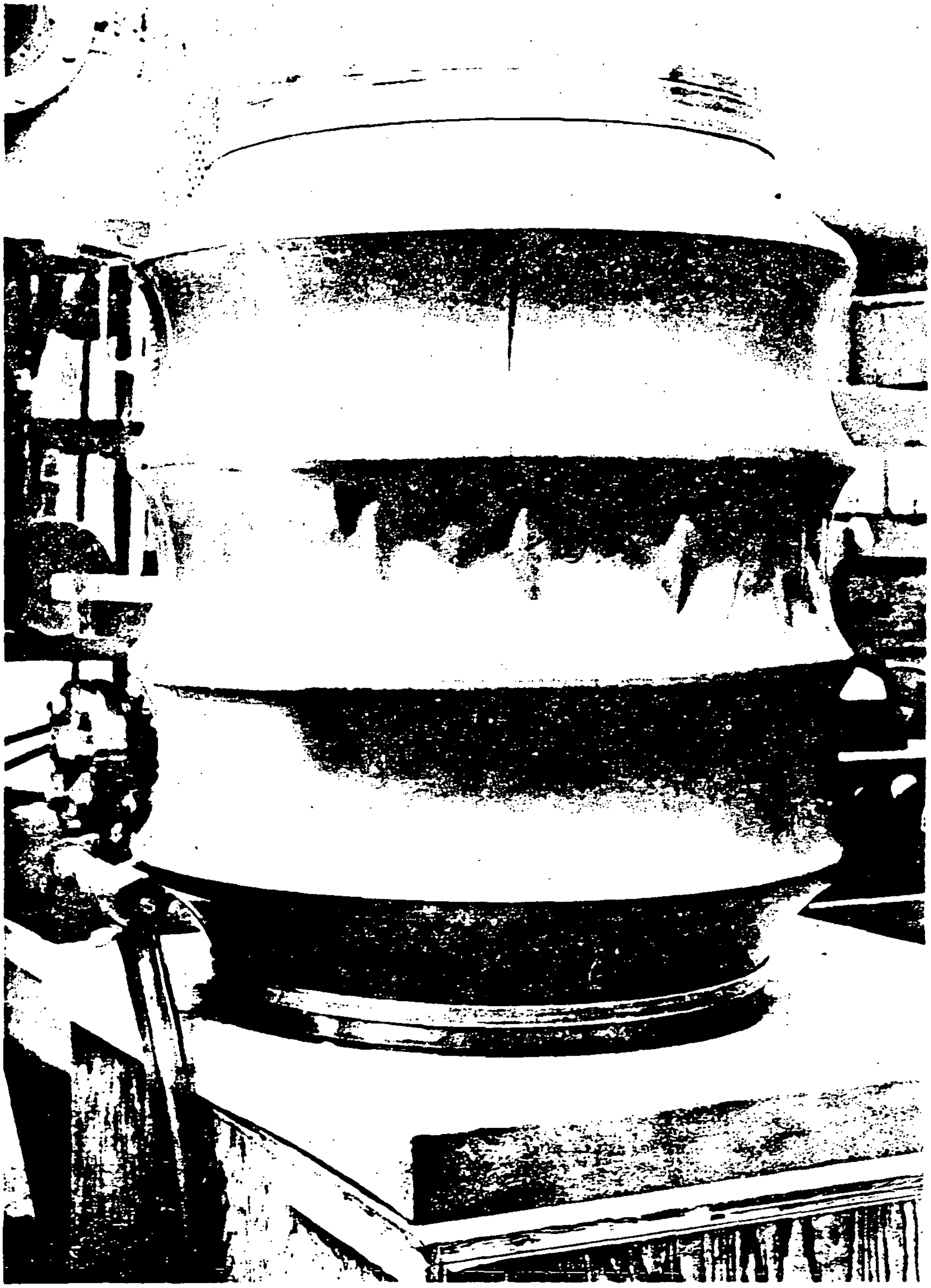


Figure 34.- Tension Membrane Vacuum Jacket (Concept 5)

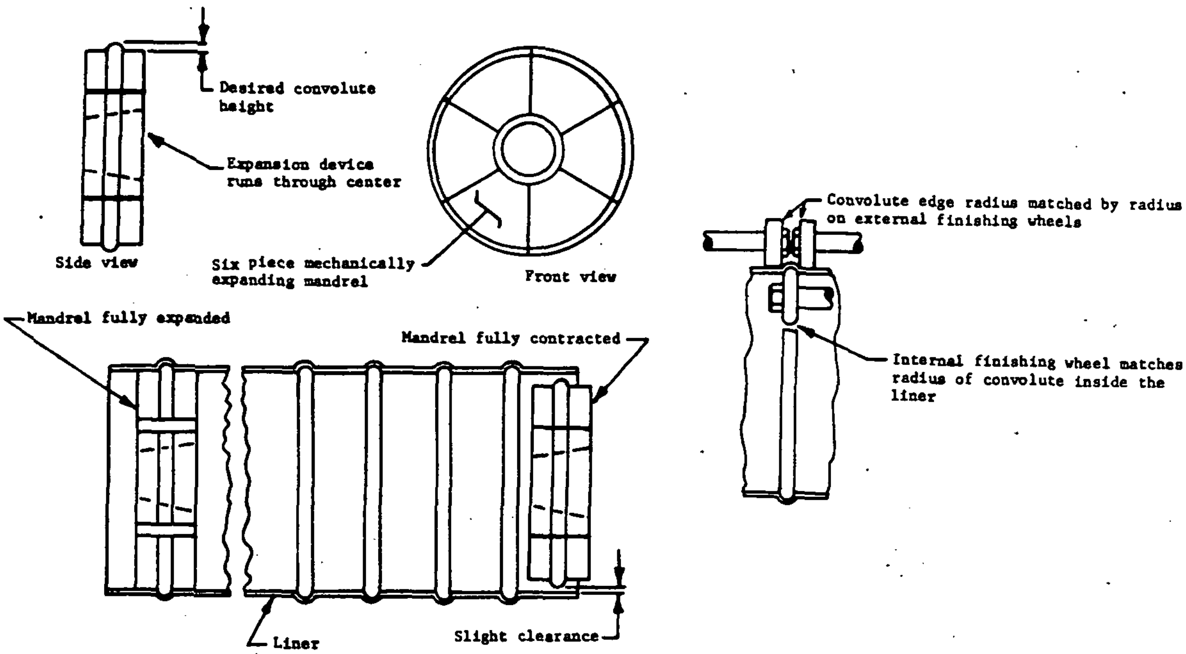


Figure 35.- External Convolute Formation Tools

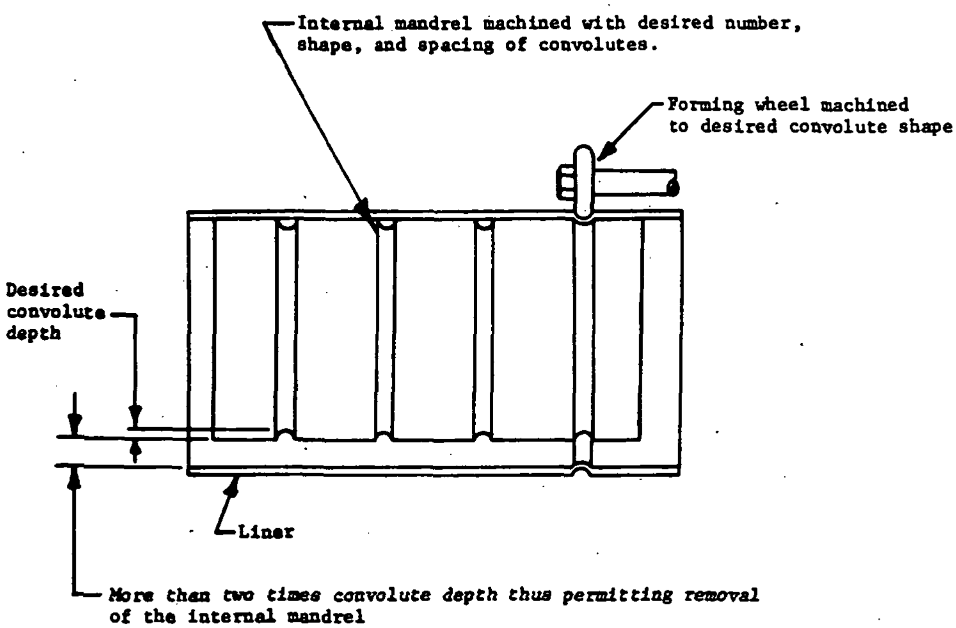


Figure 36.- Internal Convolute Formation Tools

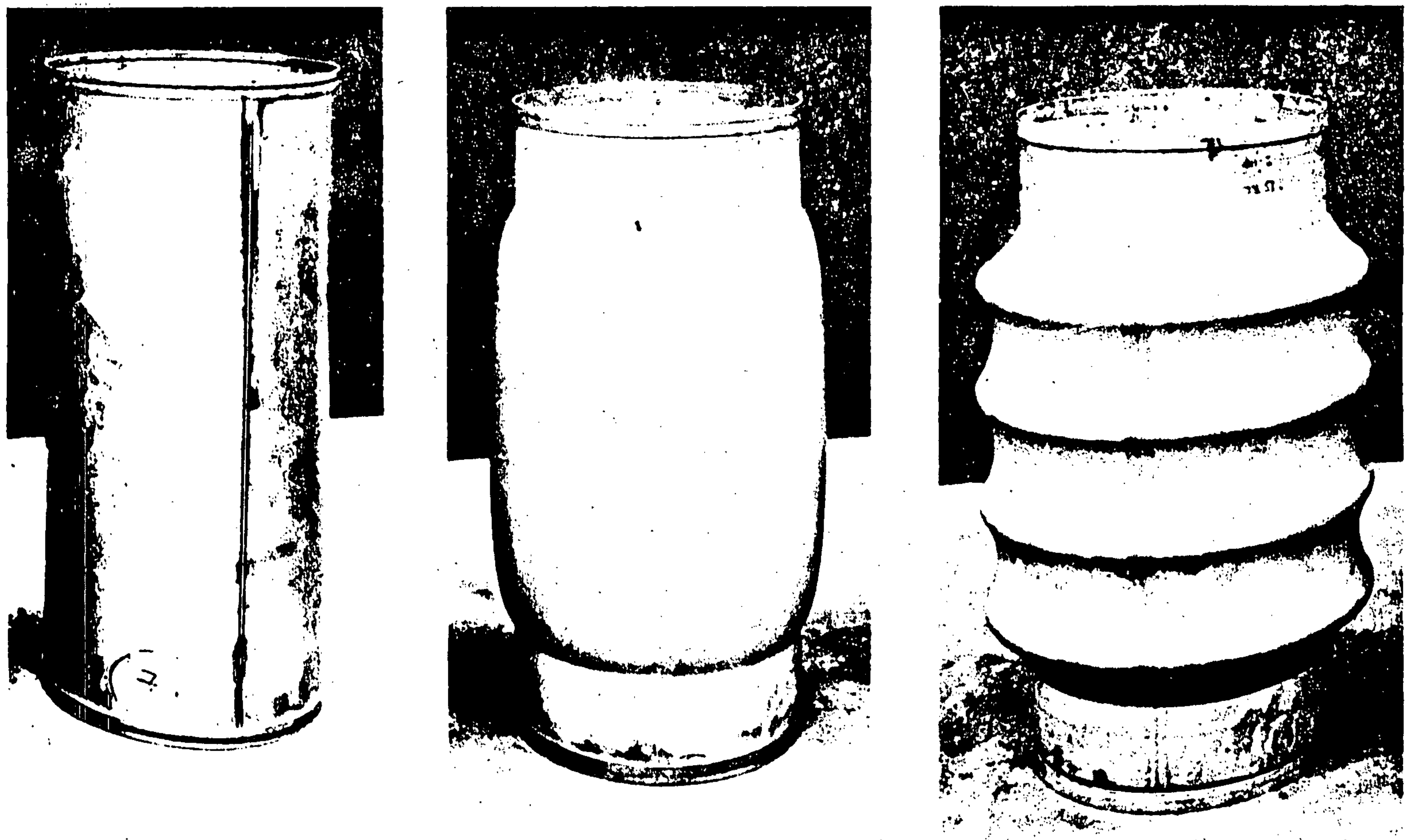


Figure 37.- Tension Membrane Bulging Sequence Preform to Postform (Concept No. 5)

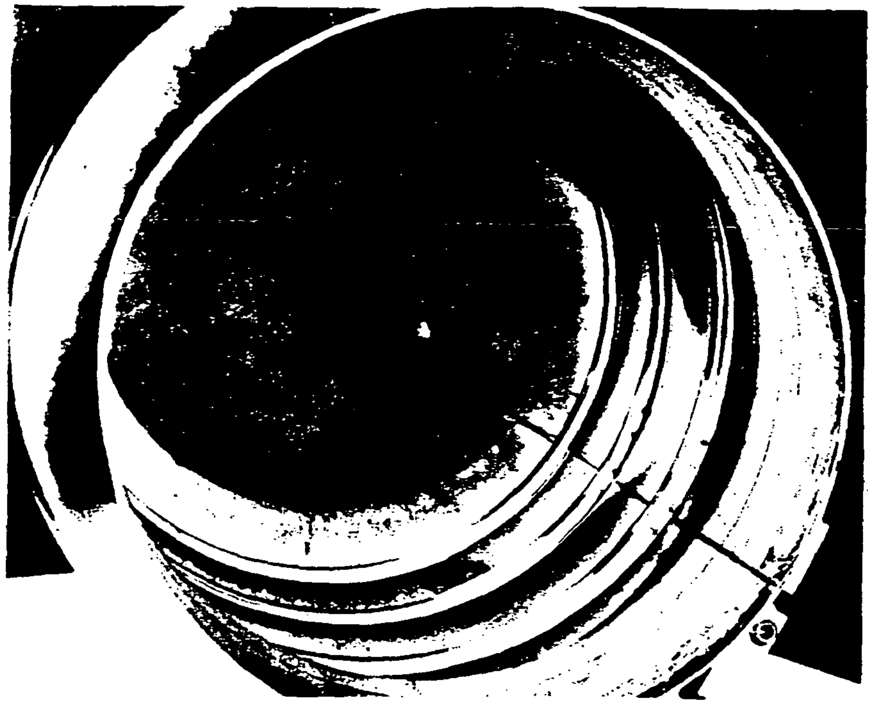


Figure 38.- Rings Installed in Tension Membrane Vacuum Jacket (Concept 5)

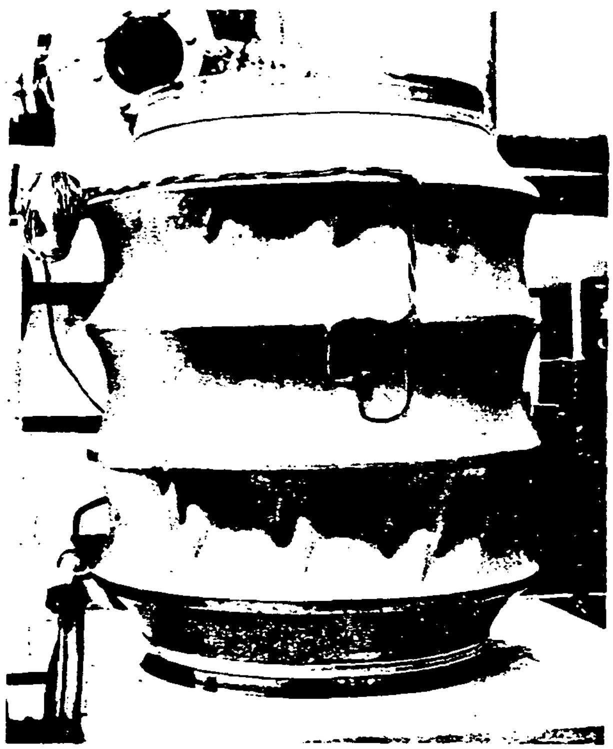


Figure 39.- Tension Membrane Vacuum Jacket Welded to Composite Inner Line (Concept 5)

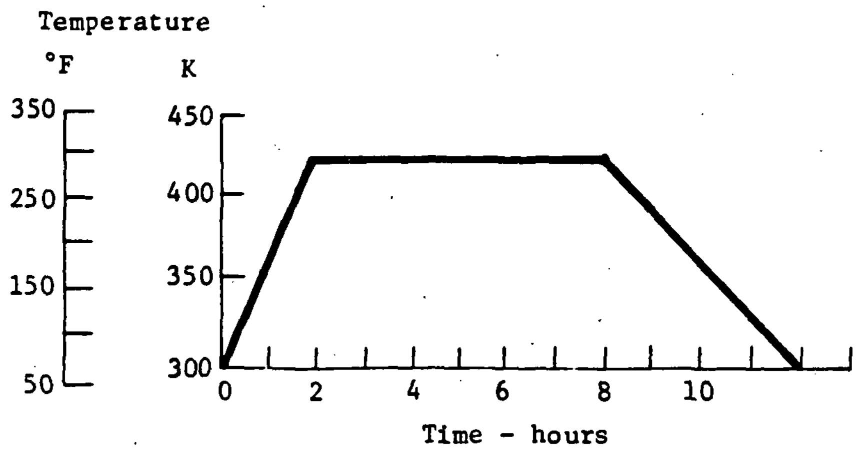


Figure 40.- Overwrap Cure Cycle for Inner Line

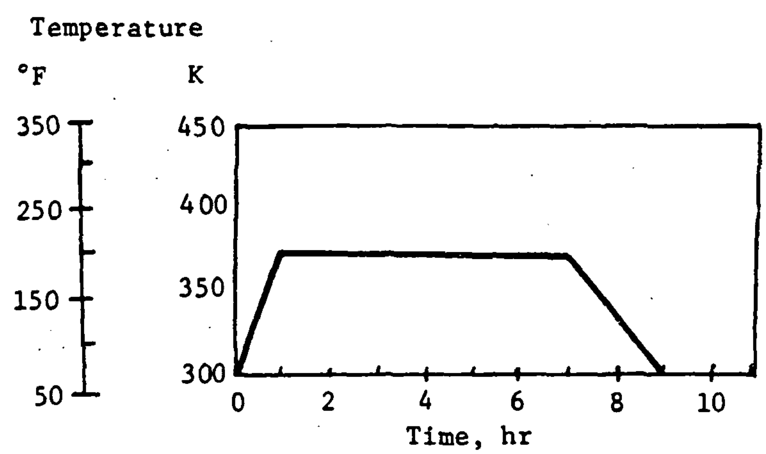


Figure 41.- Overwrap Cure Cycle for Vacuum Jackets

Figure 42.- Composite Inner Line with Center Support Pad for Vacuum Jacket Standoff

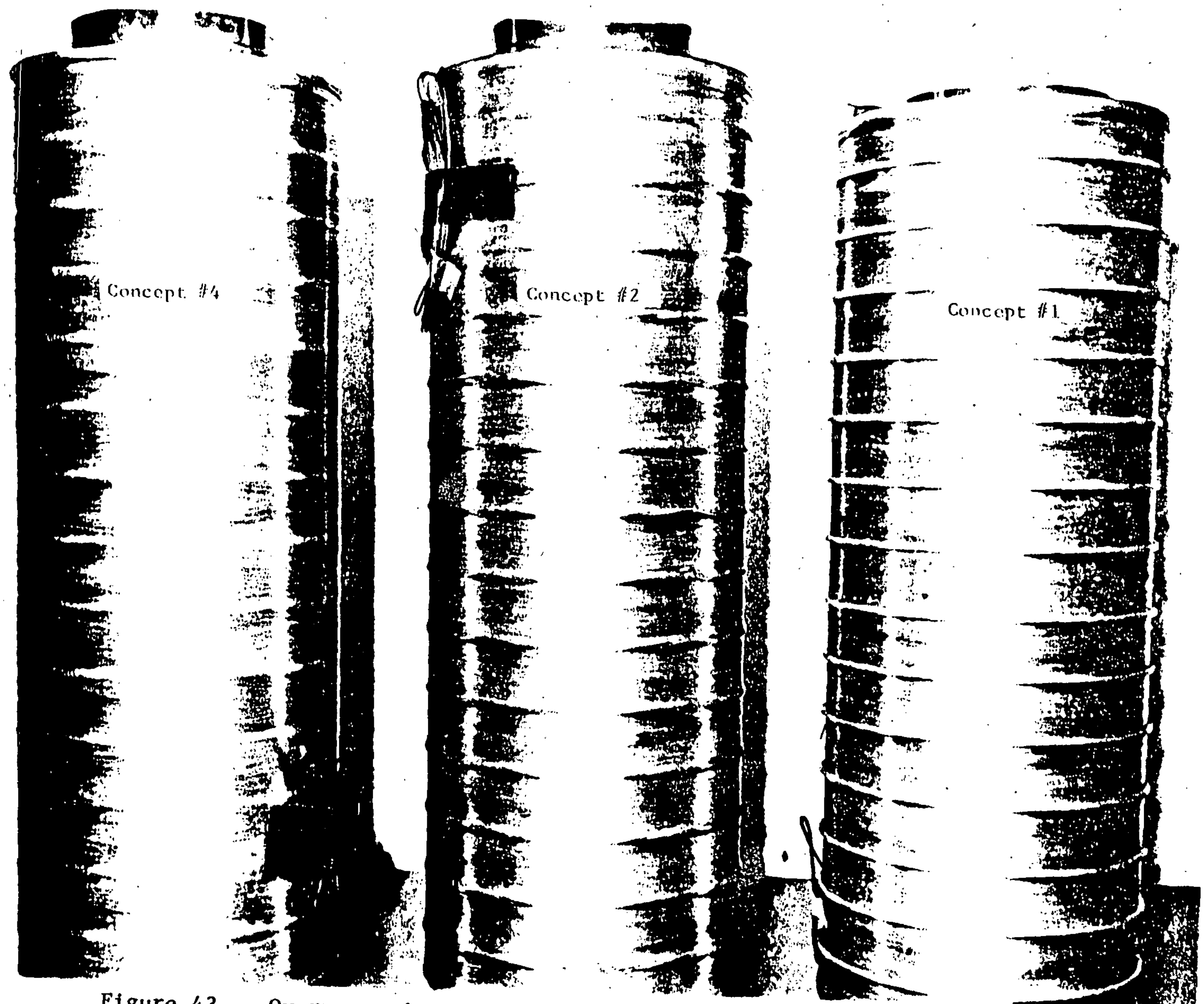


Figure 43. - Overwrapped Composite Vacuum Jackets, 20 cm (8 in.) Diameter

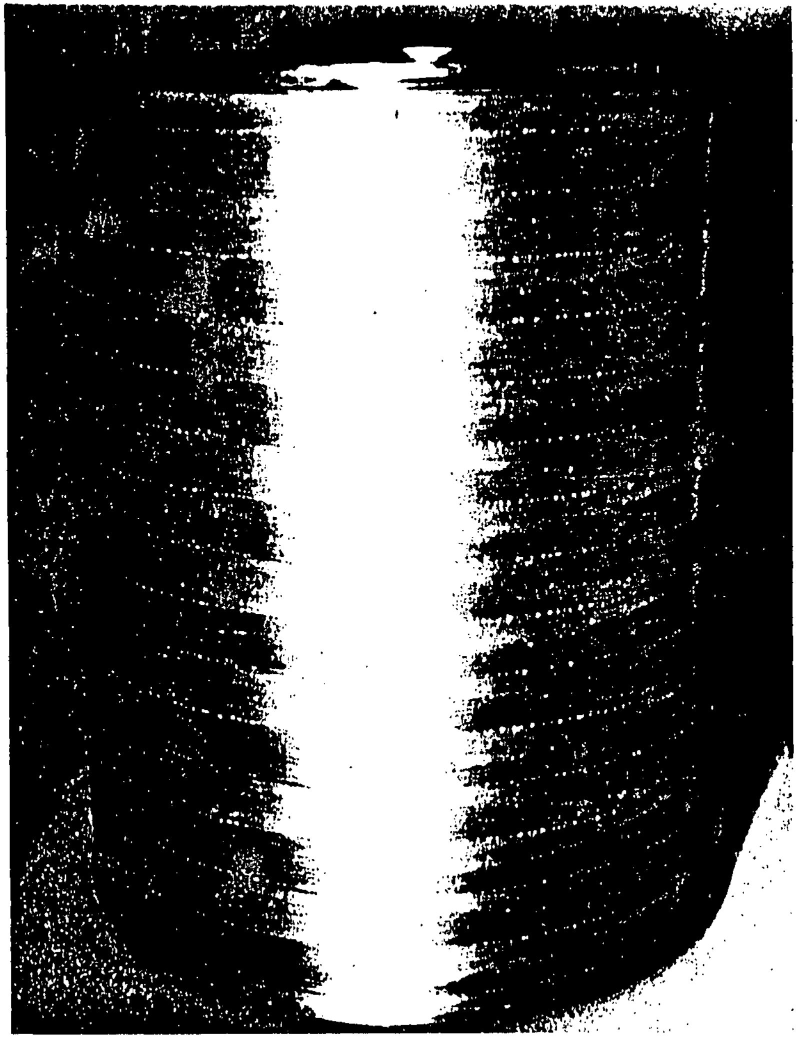


Figure 44. - Overwrapped Composite Vacuum Jacket, 46 cm (18 in.) Diameter (Concept 3)

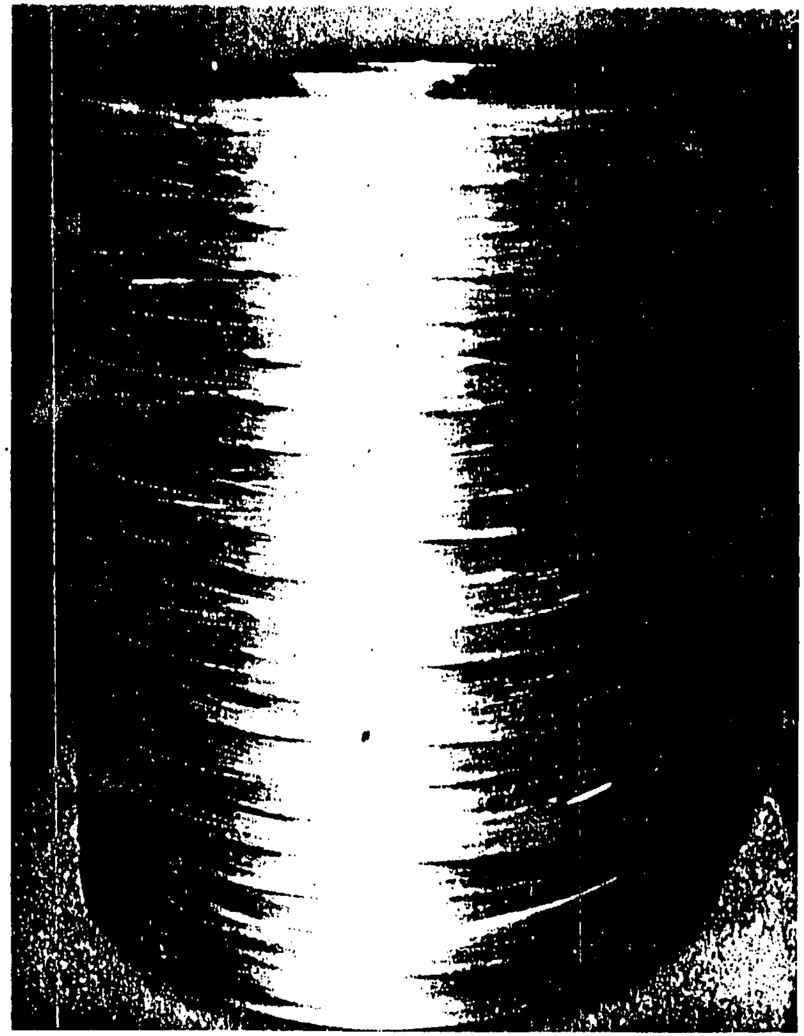


Figure 45. - Overwrapped Composite Vacuum Jacket, 46 cm (18 in.) Diameter, External Convolute (Concept 2)

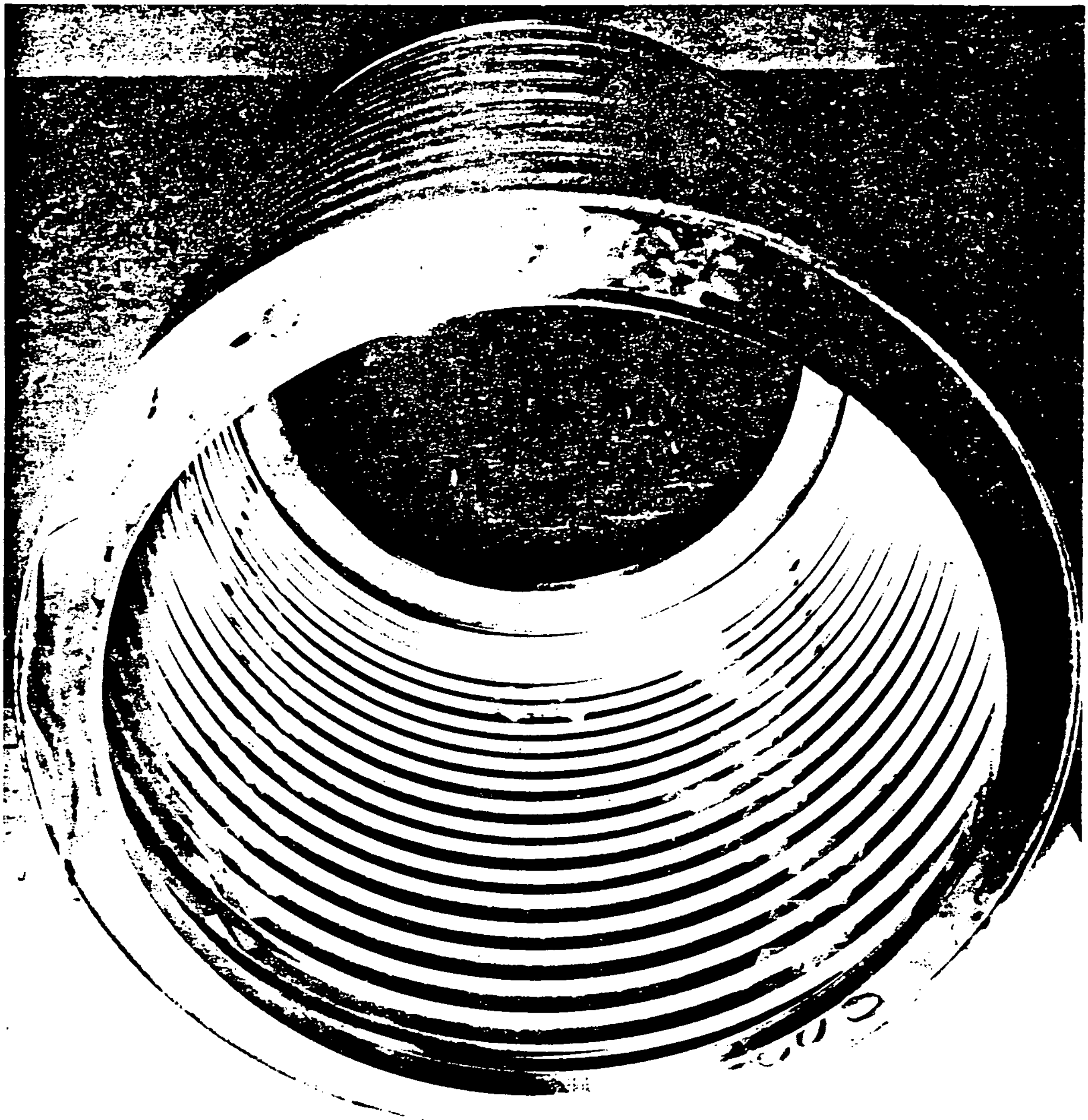


Figure 46.- Internal Hoop Support Installation (Concept 3)

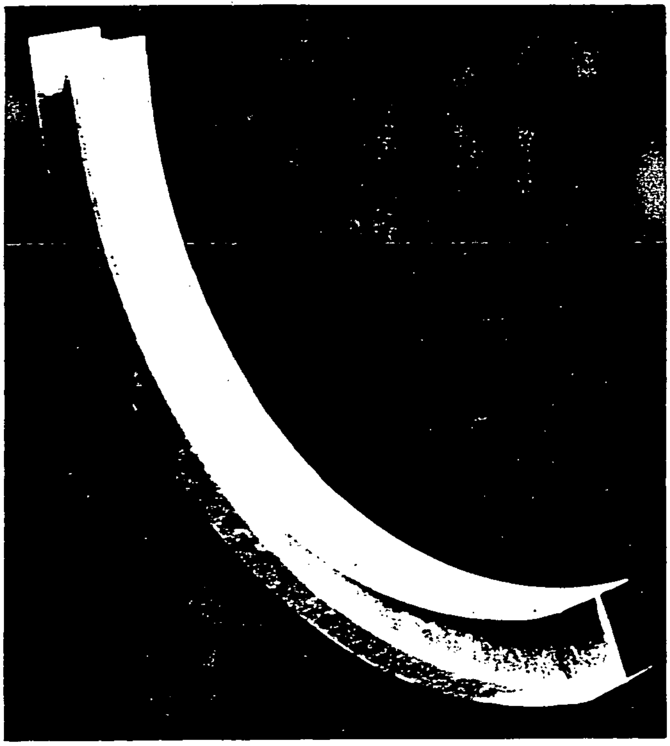


Figure 47.- Segment of Composite I-Beam Shaped Standoff

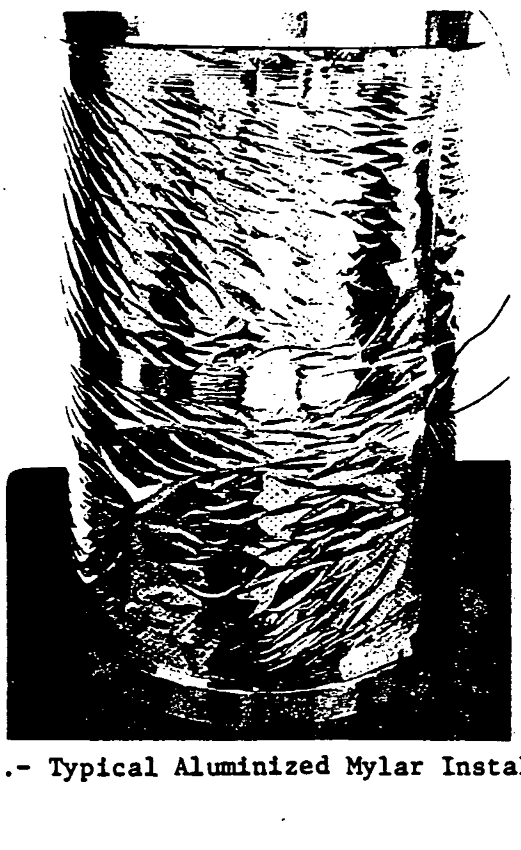


Figure 48.- Typical Aluminized Mylar Installation

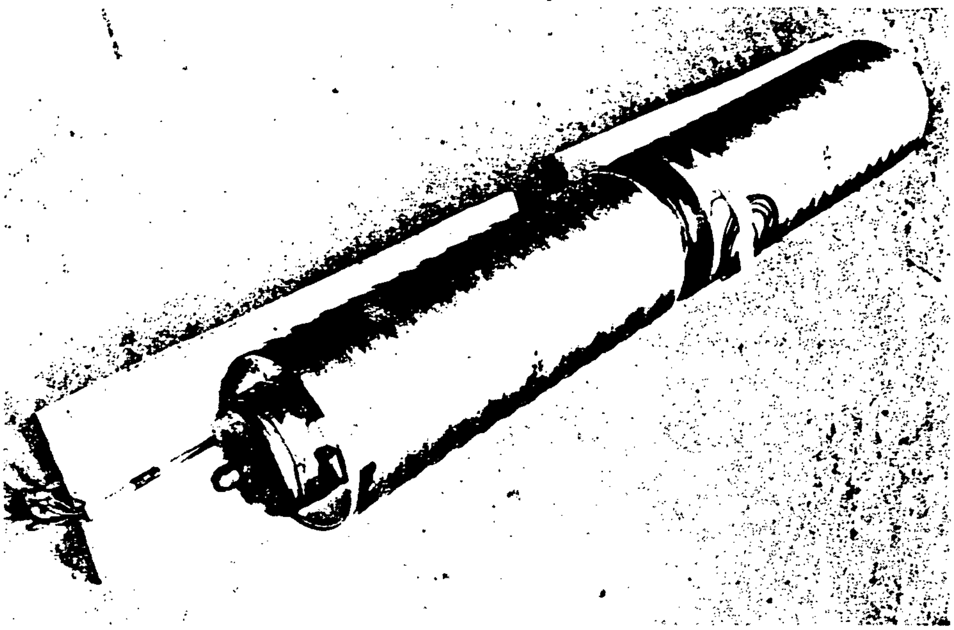


Figure 49.- Test Specimens Welded Together with Welded End Caps

TESTING

The objectives of the test program were to verify the capability of vacuum jacketed composite lines to meet design requirements of structural integrity and vacuum maintainability. To accomplish these objectives, the test items were subjected to the test programs defined in Figure 50. Testing was performed according to the test plan and in accordance with detailed test procedures. A description of the tests, test results, and correlation with analytical results are presented in this section.

Test Item Instrumentation. - Each of the test items were instrumented to provide biaxial strain measurements of both the inner line and vacuum jacketed liners. The strain gages were bonded to the inside of the liners after overwrap. Thermocouples were mounted under the last layer of overwrap on each composite section. The location of the strain gages and the thermocouples are shown in Figure 51. Additional thermocouples were installed on one of the test items to measure the temperature gradient across the various layers of overwrap.

Summary of Test Results. - Testing was performed at the Martin Marietta Corporation, Denver Division, Engineering Propulsion Laboratory from July through August 1973. A summary of the test results is provided in Table XV.

Inner Line Leak Tests. - The purpose of the leak tests was to verify the integrity of the test items before overwrap, and after overwrap and cure. The inner line leak tests were performed before the installation of the vacuum jacket by pressurizing the inner line internally (with the aid of a leak test fixture) to operating pressure with gaseous helium, and then using a helium mass spectrometer probe to detect any external leakage. The leak test data is recorded in Table XVI.

Vacuum Decay Leak Tests. - The vacuum decay rates of the vacuum jacket annuli were measured at the beginning of the test program and after each major test. The tests were performed by evacuating the annuli, closing the vacuum isolation valves, and monitoring the change in pressure level with respect to time. The vacuum decay rates thus obtained are provided in Table XVII.

The purpose of the vacuum decay leak tests was to provide a basis for assessing the integrity of the vacuum jackets and inner lines after each major test. As noted in Table XVII, the serial number F test item experienced a significant increase in vacuum decay rate indicating a failure in the pressure surge test. Inspection revealed an inner line leak. Failure of this item is discussed in the pressure surge cycle test section. Minor changes in the leak rate are attributed to test repeatability tolerances plus test facility variances.

TABLE XV. - SUMMARY OF TEST RESULTS

Serial Number	A	B	C	D	E	F	G	H	I	J	K	L	M
Nominal ID, cm (in.)	38 (15)	38 (15)	38 (15)	38 (15)	38 (15)	38 (15)	13 (5)	13 (5)	13 (5)	13 (5)	13 (5)	13 (5)	13 (5)
Concept number	2	2	5	5	3	3	2	2	4	4	1	1	
Description	External convolute		Tension membrane		Cryo-pumped		External convolute		Internal convolute		External rib		0.03 cm (0.012 in.) thick liner
Initial vacuum acquisition, hr	75		1	1	120		Jacket failed without bag		9		Bag failure		
Vacuum decay, μ/hr	84.7		1	5.2	240				82.5				2.56
Preliminary external collapse, N/cm^2 (psid)	15.2 (22)												
Strain cycle, no. of cycles	Bag failed	OK-25 Cycle	OK-25 Cycle		Bag failed	OK-25 Cycle			OK-25 Cycle				
Vacuum decay, μ/hr		70	1	9		125			123				
Surge, no. of cycles	10	10	10		10	10			10				
Vacuum decay, μ/hr		16	1			$2x10^7$			140				
Ambient acoustic, dB	160												167
Cryo acoustic, dB			160						160				
Vacuum decay, μ/day													<3
Inner line leak													zero
External collapse, N/cm^2 (psid)		15.2 (22)	12.4 (18) failed	15.2 (22)					15.2 (22) failed	15.2 (22)			

*Inner line only

TABLE XVI. - INNER LINER LEAKAGE DATA

Design concept	Serialization	Leak rate
External Convolute	A	1.3×10^{-10} scc/sec
	B	$<1 \times 10^{-10}$ scc/sec
Tension Membrane	C	1.9×10^{-5} scc/sec
	D	2.2×10^{-5} scc/sec
Internal Hoop Supports	E	$<1 \times 10^{-10}$ scc/sec
	F	$<1 \times 10^{-10}$ scc/sec
External Convolute	G	$<1 \times 10^{-10}$ scc/sec
	H	$<1 \times 10^{-10}$ scc/sec
Internal Convolutes	I	$<1 \times 10^{-10}$ scc/sec
	J	1.01×10^{-6} scc/sec
External Ribs	K	1.7×10^{-9} scc/sec
	L	6.78×10^{-6} scc/sec

TABLE XVII. - VACUUM DECAY DATA

Vacuum decay rate (μ/hr, except as indicated)				
Tube serial number	Baseline	Post strain cycle	Post pressure surge	Post acoustic
A-B	85			
B		70	16.6	60
C	1	1		
D	5	9	12	20
E-F	240			
F		125	0.07 $N/cm^2/sec$ (0.1 psi/sec)	
I-J	93	123	140	148

Vacuum Acquisition and Maintenance. - The purpose of the vacuum acquisition and maintenance tests was to demonstrate the capability of the vacuum jacketed composite lines to meet current state-of-the-art vacuum maintenance criteria. The vacuum criteria for the Saturn cryogenic feedlines was a maximum vacuum limit of 100 μ and a 5 μ/day allowable rise rate. This criteria was adopted for evaluation of the vacuum jacketed composite lines.

Because of the outgassing potential of the instrumentation wiring in the vacuum annulus, and of the long time duration required for bakeout and vacuum decay measurement, the vacuum acquisition and maintenance testing was performed on only one of the test items. The test item selected for this testing consisted of a 20 cm (8 in.) diameter vacuum jacket with a 0.03 cm (0.012 in.) thick liner. This vacuum jacket was fabricated to replace one of the vacuum jackets that had failed in initial evacuation. A 13 cm (5 in.) diameter composite inner line was salvaged from the failed test item to make up the vacuum jacketed line assembly. The composite surface of the inner line was cleaned with freon and all instrumentation wiring was removed before assembly. After welding, the vacuum jacketed line assembly was leak tested by connecting the helium mass spectrometer to the vacuum annulus and placing the line assembly in a helium filled plastic bag. No leaks were detected.

A series of six vacuum acquisition and decay tests were performed with changes being made to the test setup between tests as shown in Figure 52. The data from these tests is provided in Table XVIII. Significant improvements in vacuum decay rate were achieved by the changes in the test setup, but the data was not conclusive. The decay rate of 9 μ/day was suspected to be largely due to system leakage.

Leak tests were repeated and a leak was discovered at the point where the vacuum gage plug screws into the vacuum source tube (Fig. 52). This leak was repaired. In order to determine if the vacuum decay rate was caused by system leakage or outgassing, the tube assembly was placed in a vacuum chamber to eliminate the delta pressure across the vacuum jacket. Thus, by controlling the external environment to a pressure near that of the vacuum annulus, the potential for leakage was eliminated and all pressure decay could be attributed to outgassing. The tube was evacuated to 12 μ and decay rate was monitored for eight days. The results of this test are plotted in Figure 53.

As noted from Figure 53, the decay rate was insensitive to chamber pressure, indicating that all system leakage had been repaired. After the fifth day, the decay rate became less than the 5 μ/day allowable. By the eighth day, the decay rate curve was becoming flat and it appeared that the outgassing was about to stabilize well below the 100 μ limit.

Table XVIII. - VACUUM ACQUISITION AND DECAY TEST DATA

Test No.	Pump-down time, hr	Vacuum level achieved, μ	Test duration (vacuum decay measurement), hr	Vacuum decay rate, μ/day	Discussion or conclusions
1	24 (ambient temperature)	0.6	N/A	N/A	Facility did not provide vacuum lockup capability. Pump-down to assure vacuum acquisition.
2	27 (ambient temperature)	0.6	40	14.6	Straight line decay rate.
3	96 (in oven at 338°K) (150°F)	0.033	22	27	Straight line decay rate. Leakage suspected in the system. Vacuum gage too sensitive to determine decay rate.
4	3 (ambient temperature)	6	24	42	Leakage suspected in system.
5	1	10	24	31	Setup changed. Leakage still suspected.
6	48 (in oven at 338°K) (150°F)	2	96	9	Straight line decay. Setup improvement reduced leakage.

To verify the conclusion of the decay test previously discussed, the tube was baked out again and the decay test was repeated. The bakeout was at 359K (187°F) for 24 hours and the decay test was from 0.5 μ to 210 μ in 82 days at an average rate of 2.56 μ/day (Fig. 54). As in the previous decay test, the tube was placed in a vacuum chamber to allow study of leak rate versus external pressure. Again, the decay rate was relatively constant at external pressure of 610, 200, or 1 torr, confirming the tube to be leak free. The decay was therefore, caused by outgassing, probably of one of the cleaning solvents. Most solvents vaporize at approximately 100 torr (100,000 μ) and the decay test would have to be continued indefinitely to reach this pressure and prove the outgassing source.

It was concluded that the vacuum jacketed tube had negligible leakage and an outgassing rate of 2.56 μ/day. It was also assumed that the outgassing was due to residual solvents that could be eliminated by more extensive bakeout.

Strain Cycle Test. - The objective of the strain cycling test was to verify the structural integrity of the vacuum jacketed composite lines while being subjected to thermal and internal pressure stresses expected during the launch and boost phases of the Space Shuttle mission. The test items were subjected to the following sequence:

1) Prechill inner lines by filling with liquid nitrogen.

2) Drain inner lines and fill with liquid hydrogen.

3) Pressurize the inner lines to operating pressure 69 N/cm^2 (100 psi) for the 38 cm (15 in.) diameter lines and 42 N/cm^2 (60 psi) for the 13 cm (5 in.) diameter lines.

4) Drain the liquid hydrogen.

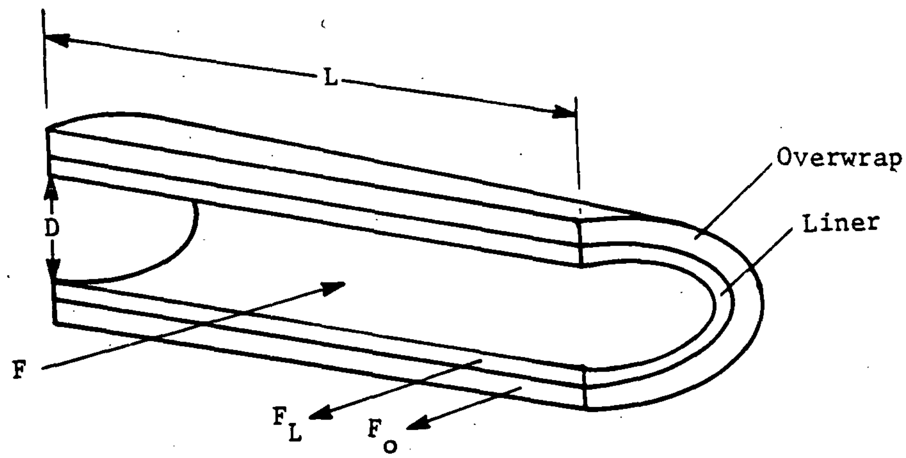
5) Warm to room temperature by flowing hot gaseous nitrogen through the inner lines.

The test was performed on test specimens A-B (external convolutes); C-D (tension membrane), E-F (internal hoop supports) and I-J (internal convolutes). A vacuum was established in each of the vacuum jackets except E-F, which was back filled with CO_2 to 8.1 N/cm^2 (11.8 psi) absolute for cryopumping evaluation. The test setup is shown in Figures 55 and 56.

The test was terminated after 26 cycles because of problems experienced with the vacuum bags over the composite vacuum jackets. After repeated cycles, the vacuum bags accumulated moisture and lost vacuum integrity. The A half of the A-B test specimen experienced a vacuum jacket buckling failure for this reason. After this failure, the test was continued with the B half.

Strain Data Correlation. - Strain data was recorded for both the inner line and the vacuum jacket during strain cycling tests. The actual inner line liner hoop strains averaged 1900 μcm/cm at 69 N/cm^2 (100 psi), whereas the predicted hoop strain at this pressure is 4150 μcm/cm. Although the strains appear to be incomparable (by a factor of 2.2), they merely reflect the conservative philosophy used during design and fabrication. The inner line liner axial strains exhibited a similar relationship.

The predicted inner line liner strains were calculated by sectioning the inner line as shown into a free body.



The total force due to pressure acting on the free body (F) is equal to the pressure (P) diameter (D) length (L) and must be balanced by the forces exerted by the liner (F_L) and the overwrap (F_o).

$$F = F_o + F_L = PDL$$

C-2

Considering the liner and overwrap individually

$$\text{Stress (S)} = \frac{\text{Force}}{\text{Area}}$$

Therefore $S_o = \dfrac{F_o}{2t_oL}$ and $S_L = \dfrac{F_L}{2t_LL}$

or $F_o = 2S_o\, t_oL$ and $F_L = 2S_Lt_LL$

Substituting into the force equation above:

$$PDL = 2S_o\, t_oL + 2S_L\, t_L\, L$$

By definition, the modulus of elasticity (E) $= \dfrac{\text{Stress (S)}}{\text{Strain (e)}}$

or $S = Ee$

Substituting into the PDL equation:

$$PDL = E_o\, e_o\, 2t_oL + E_L\, e_L\, 2t_LL$$

But $e_o = e_L$ because the overwrap and liner are bonded and must move together. Setting $e_o = e_L$ and rearranging yields:

$$e = \frac{PD}{E_L\, 2t_L + E_o\, 2t_o}$$

Substituting actual values and solving:

$$e = \frac{69 \times 38}{(20 \times 10^6)\ (2)\ (0.013) + (1.1 \times 10^6)\ (2)\ (0.0508)}$$

$$e = 4150\ \mu\text{cm/cm (hoop)}$$

In conclusion, the strain cycle test results reflect adequate structural margin when the vacuum jacketed composite lines are subjected to operating pressures at cryogenic temperatures.

Temperature Data Taken During Strain Cycling Test. - During the cryogenic portion of the strain cycle test, the specimen pairs were filled with liquid hydrogen. In addition to providing a realistic low temperature use situation, the test provided data from which the temperature distribution through the composite can be determined. Specimen B had thermocouples located in the inner line as shown in Figure 57 and from these thermocouples the temperature distribution through the inner line is plotted in Figure 58.

For the same liquid hydrogen test the radial temperature distribution through an end closure is plotted in Figure 59. The location of thermocouples used to make this plot are shown in Figure 60.

Pressure Surge Cycle Test. - The test specimens were subjected to pressure surge tests to assure structural integrity when subjected to surges simulating the closing of a prevalve. The surge cycle consisted of pressurizing the 13 cm (5 in.) diameter lines to 41 N/cm^2 (60 psia) and the 38 cm (15 in.) diameter line to 64 N/cm^2 (100 psia) in a time span of less than one second, while at cryogenic temperature. The test specimens were installed in the test setup shown schematically in Figure 61 and pictorially in Figure 62. The A-B pair was installed first and was subjected to one surge cycle, and then the C-D and E-F pairs were also installed for 10 additional cycles. After the large diameter pairs were tested simultaneously, the I-J specimen was subjected to 10 surge cycles.

The surge cycles were performed by filling the test specimens and the ullage with LN_2, pressurizing the ullage to 140 N/cm^2 (200 psi), releasing this pressure into the specimen, and venting the specimen rapidly (by burst disc) when operating pressure was reached. Specimen pressurization was accomplished in approximately one second and depressurization required approximately 0.1 second.

No apparent damage or deterioration of the specimens was observed during posttest inspection of the vacuum jackets. However, during the postsurge vacuum decay leak test, a gross leak, 0.07 N/cm^2 (0.1 psi/sec), was found to exist in the inner line of tube F. Inspection revealed severe buckling of the inner line liner, and the leak was located at a permanent crease in one of the buckles. A review of the log history showed that prior to this time the F tube had been subjected to strain cycles, surge cycles, vacuum decay tests, and a CO_2 cryopump test. During the strain cycling and surge tests, the ambient temperature annulus pressure had to be reduced from 8.5 N/cm^2 (12.3 psia) to local ambient pressure of 8.1 N/cm^2 (11.8 psia) to prevent implosion of the inner line liner. During the vacuum decay tests, the F tube decay rate was greater than that of the other tubes.

During the cryopump test, the annulus was evacuated and backfilled with CO_2 to 8.1 N/cm^2 (11.8 psia), and the inner line was filled with LN_2. During the LN_2 fill, the annulus pressure cryopumped to approximately 66.5 N/m^2 (500 μ of Mg), and then increased to greater than 266 N/m^2 (2000 μ) (off-scale). Subsequent leak tests revealed the leak in the inner line liner. It was concluded that the inner line failure occurred during the cryopump test.

The above observations lead to the following hypothesis of failure: the inner line leakage into the cryopumping annulus caused a pressure buildup in the annulus when the line returned to ambient temperature sufficient to buckle the inner line liner. Repeated cryogenic/pressure cycles worked the buckles until failure occurred.

Acoustic Test. - The A-B specimen pair and the M specimen were subjected to an ambient acoustic test; the C-D and I-J pairs were subjected to a cryogenic acoustic test. The tests were performed by installing the pair in the acoustic chamber shown in Figure 63 and instrumenting as shown in Figure 64. For the C-D and I-J specimen tests, the cryogenic supply and vent system, shown in Figure 65, was installed, and the specimen pair was filled with LN_2 and allowed to vent to atmosphere while the test was performed. The chamber was secured and the acoustic horn was operated to create an acoustic environment of an overall sound intensity of 159.5 (167.5 for M) dB with a frequency distribution as shown in Figure 66 (Fig. 67 for M).

The specimen pairs sustained no apparent damage from the acoustic exposure. Representative accelerometer and strain gage spectral density plots are shown in Figures 68 and 69, respectively. The peak frequency and g rms level for each accelerometer, and the peak frequency and strain (rms) for each strain gage, are tabulated in Table XIX.

External Pressure Collapse Test. - All test specimens that were joined together such as A, B, etc, for the previous testing were cut apart at the weld which joined the pairs and were subjected to external collapse testing separately. The individual test specimen was installed in a pressure chamber as shown in Figures 70 and 71, and applying gas pressure outside of the ambient temperature vacuum jacket while the vacuum inside the annulus was monitored. The collapse pressure was established as that pressure at which pressure in the vacuum annulus started to increase. In addition, inner line and vacuum jacket strain was continuously monitored during the test.

TABLE XIX.- ACOUSTIC TEST, PEAK FREQUENCY ACCELEROMETER AND STRAIN GAGE DATA

Specimen	Level, dB	Accelerometer			Strain Gage		
		No.	Peak Frequency, Hz	Strain, g rms (g^2/Hz)	No.	Peak Frequency, Hz	Strain, rms (μ cm/cm)
A-B	160	1	62	10.61	3B	70	33
		2	190	12.73	4B	Min	55
		3	68	11.03	7B	22	15
		4	220	14.42	8B	48	45
		5	210	9.76	9B	100	27
		6	210	24.04	10B	68	30
		7	280	14.85			
		8	260/740	24.75			
		9	240	11.88			
C-D	160	1	830	12.73	1D	220	42
		2	240	9.55	2D	220	100
		3	1600	13.57	11C	62	45
		4	240	14.14	12C	500	240
		8	270	12.3			
		9	190	8.27			
I-J	160	1	650	6.75	1-I	48	30
		2	310	4.88	2-I	Min	35
		3	550	5.09	5-I	48	10.5
		4	550	11.45	6-I	68	70
		5	550	6.36	9-I	62	13.5
		6	680	13.79	10-I	64	25
		7	520	9.33			
		8	53	6.36			
		9	53/700	5.94			
M	167	1	80	2.4			
		2	360	23			
		3	610	14			
		4	35	13			
		5	300/750	38			
		6	300/1000	46.5			
		7	580	22			

The B, D, and J tubes successfully withstood an external pressure 15.2 N/cm^2 (22 psi) greater than annulus pressure for five minutes. The C tube failed at 12.4 N/cm^2 (18 psid) due to an axial compression failure of the inner line. Photographs of the C tube after failure are provided in Figures 72 and 73. The I tube failed at 15.2 N/cm^2 (22 psid) while being pressurized to 24.8 N/cm^2 (36 psid) due to implosion of the jacket liner.

It was concluded from these tests that the tension membrane concept (C and D) will withstand the design external pressure when supported externally in the axial direction, as they would be in a normal application. The glass overwrap concepts (B, I, and J) will withstand design external pressure if the nylon bag technique is used to transfer the load from the bond to the glass.

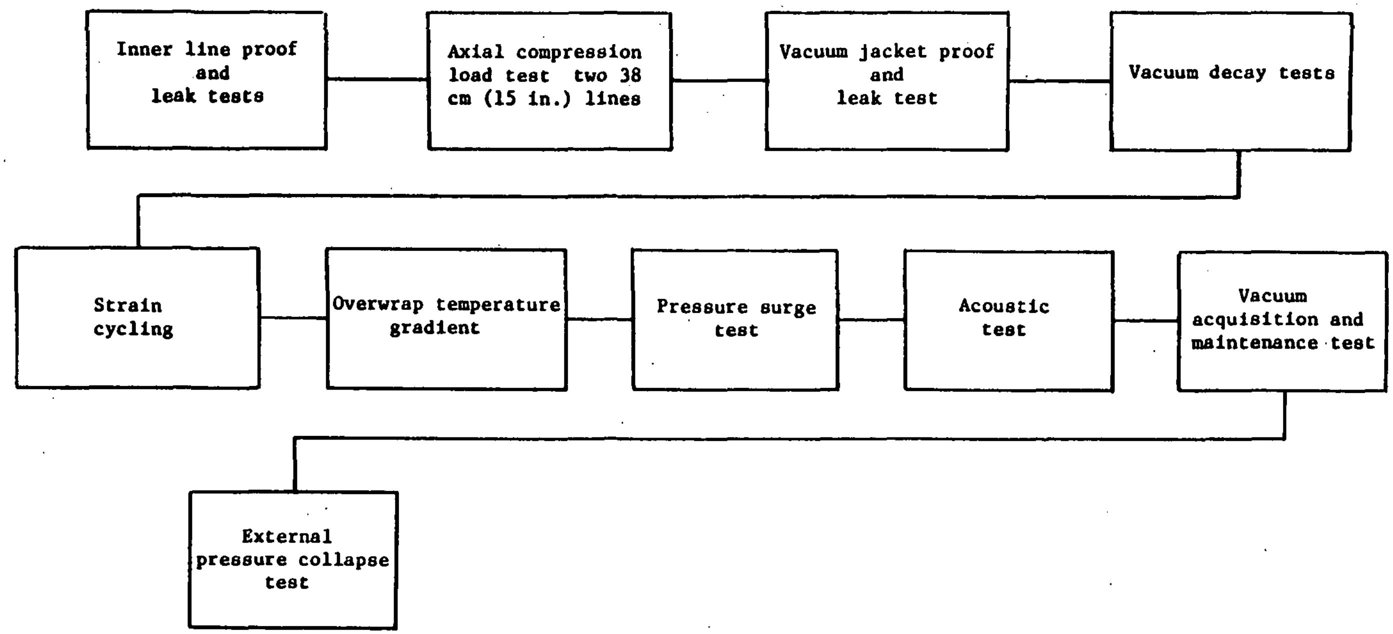


Figure 50. - Testing Definition and Sequence

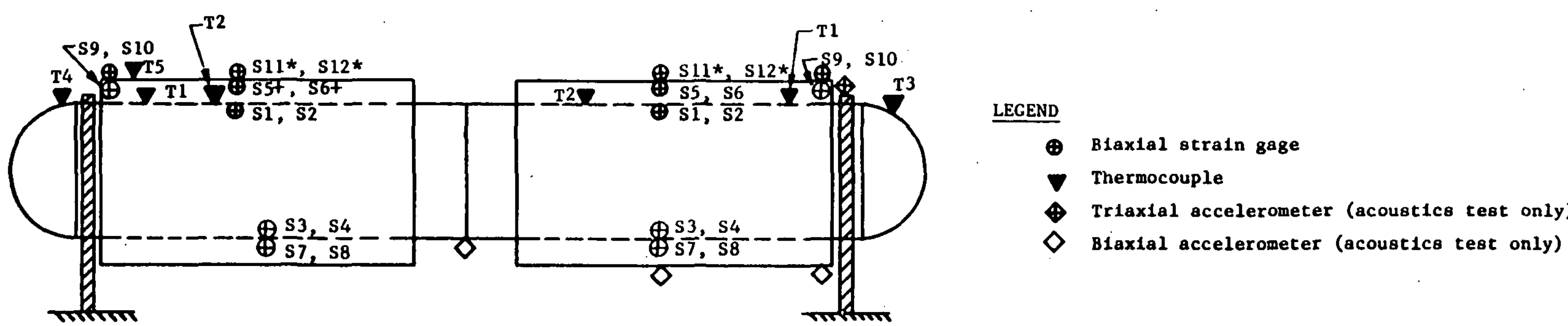


Figure 51. - Test Item Instrumentation

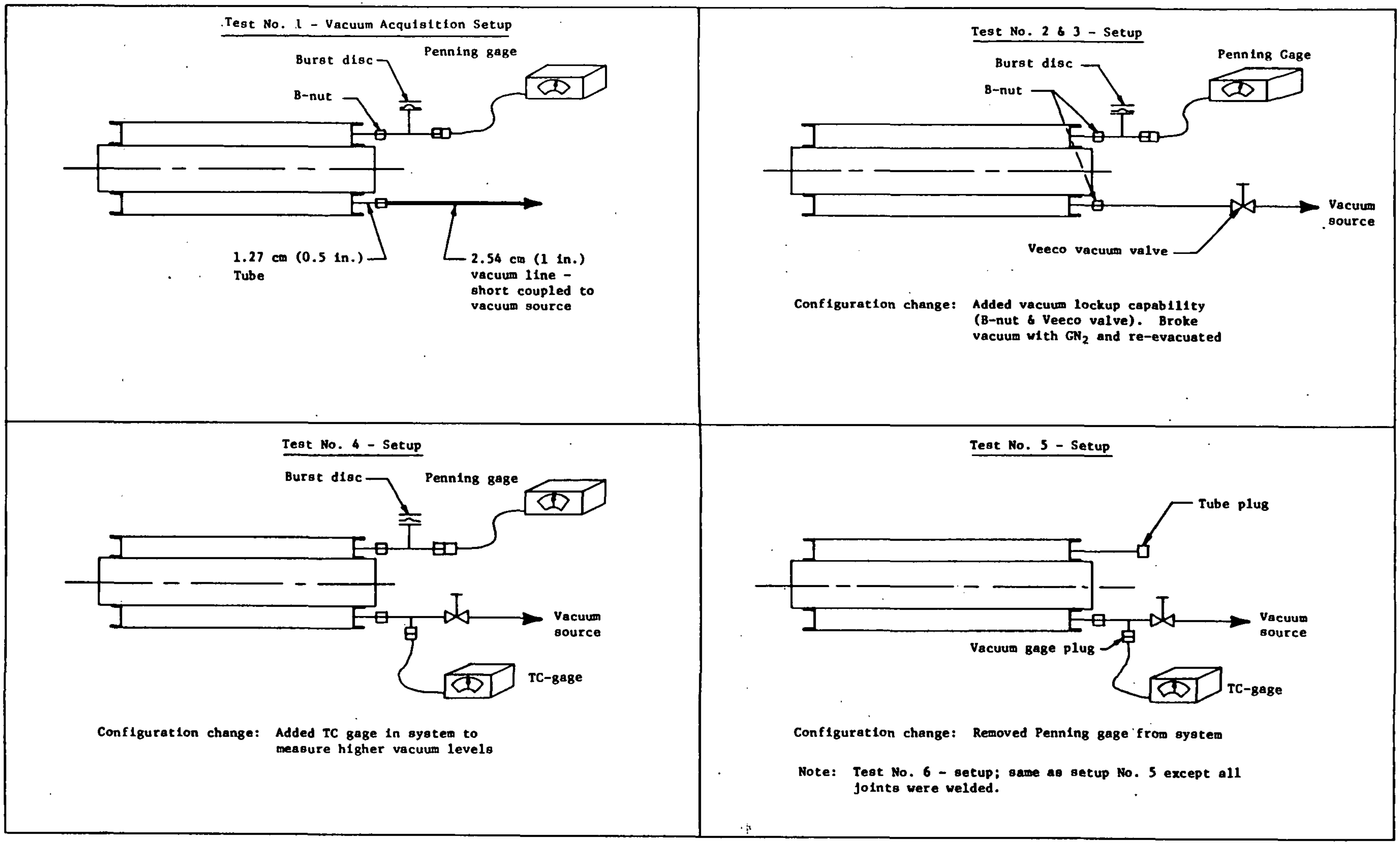


Figure 52. - Vacuum Acquisition and Decay Test Setup

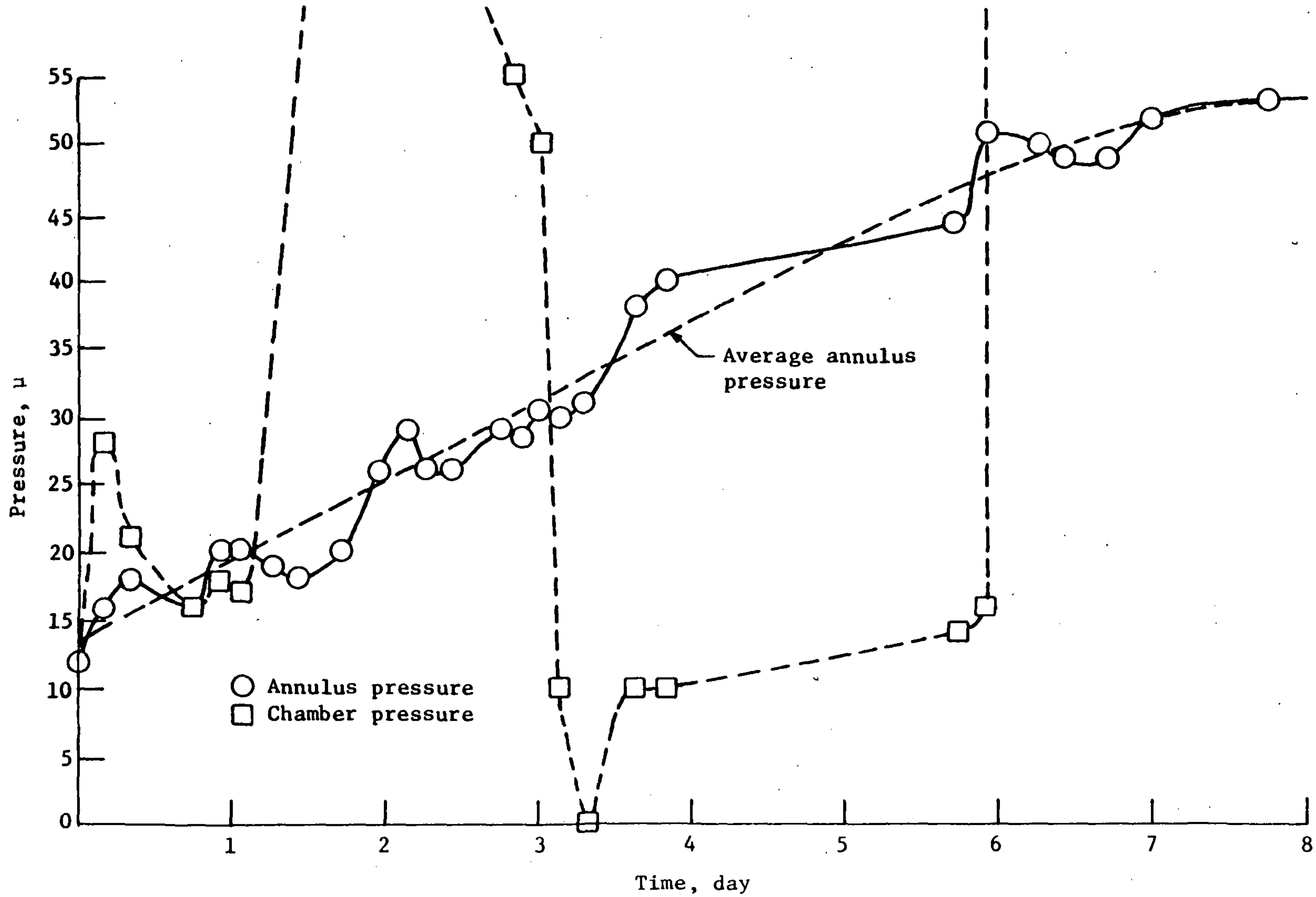


Figure 53. - Vacuum Outgassing Test

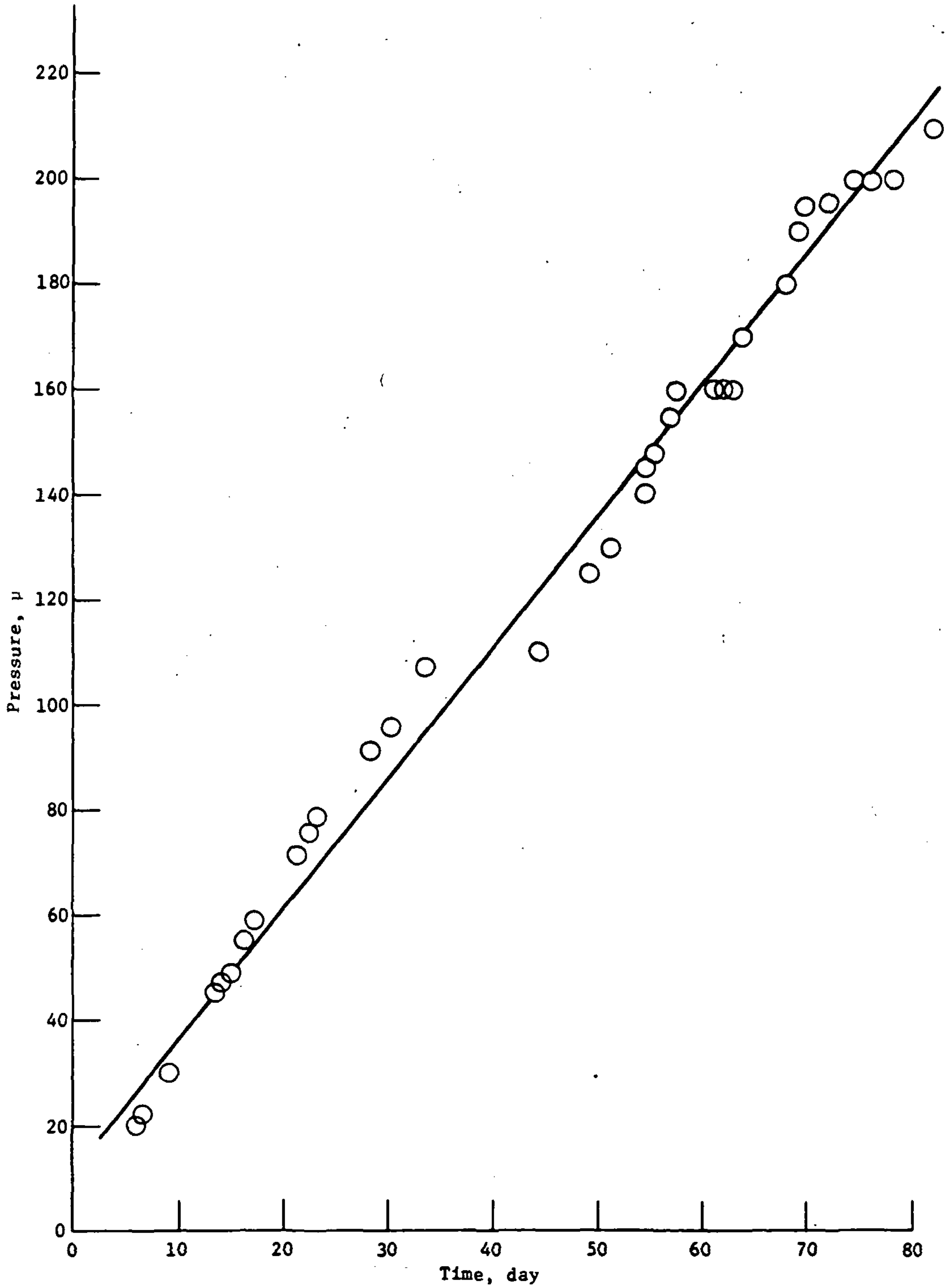


Figure 54. - M-Tube Vacuum Decay Test (82 Days)

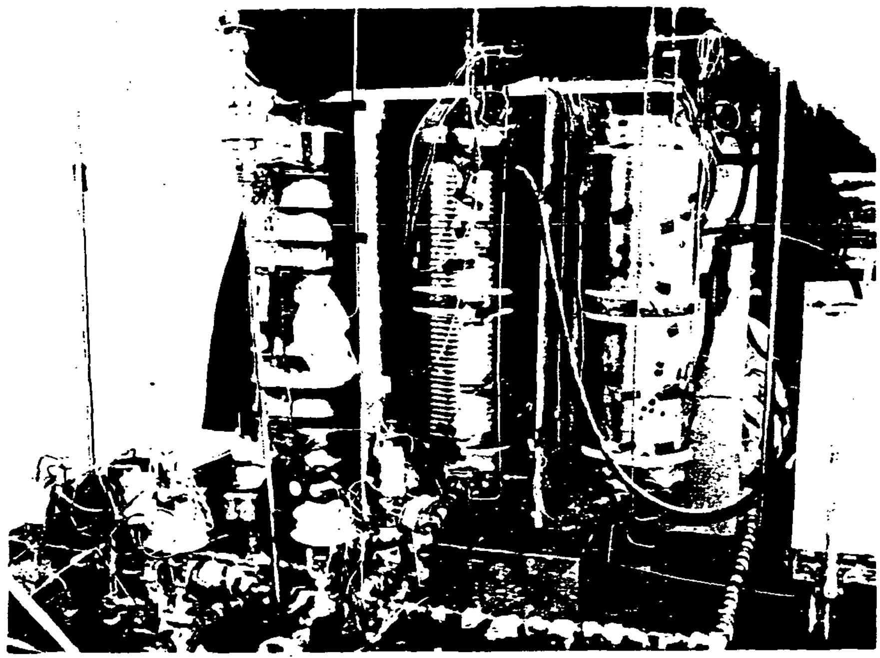


Figure 55. - Strain Cycle Test Setup Showing 38 cm (15 in.) Diameter Tubes

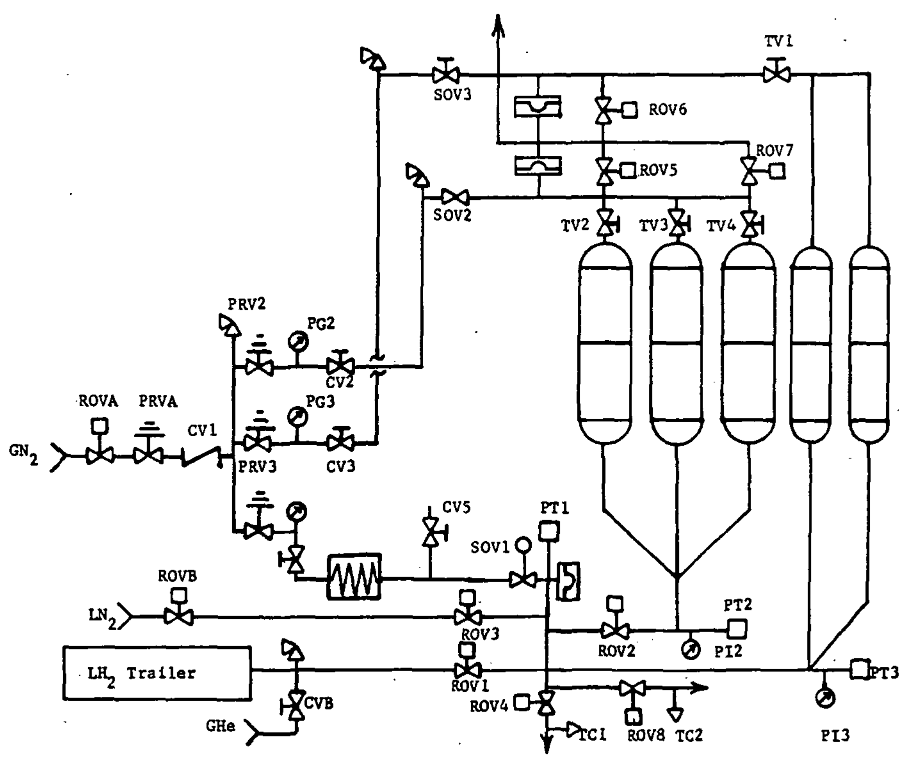


Figure 56. - Strain Cycle Test Schematic

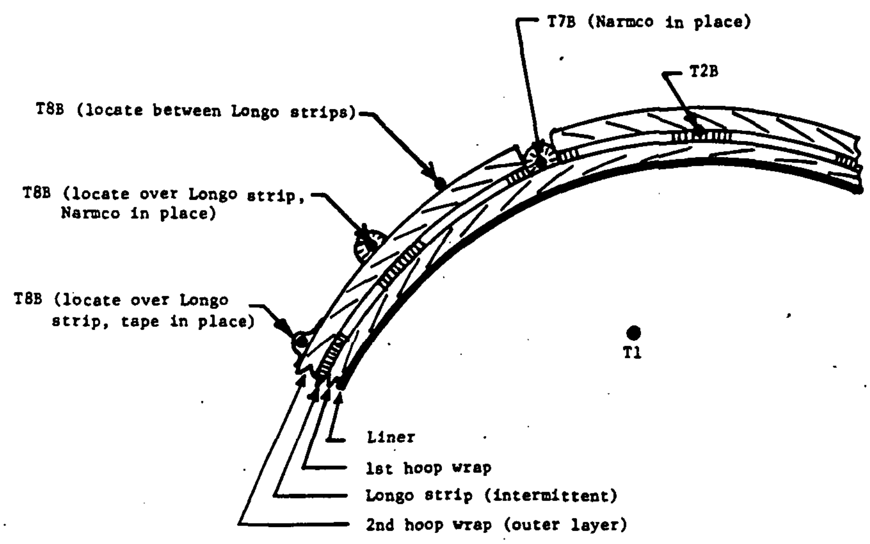


Figure 57. - Thermocouple Location for Inner Line Temperature Distribution

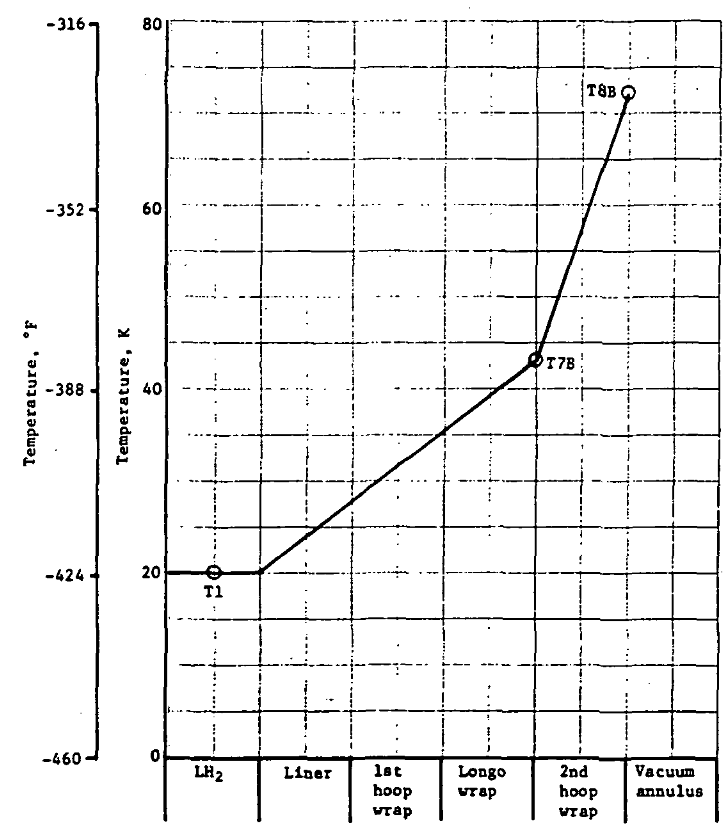


Figure 58. - Temperature Profile of 38 cm (15 in.) Inner Line (B)

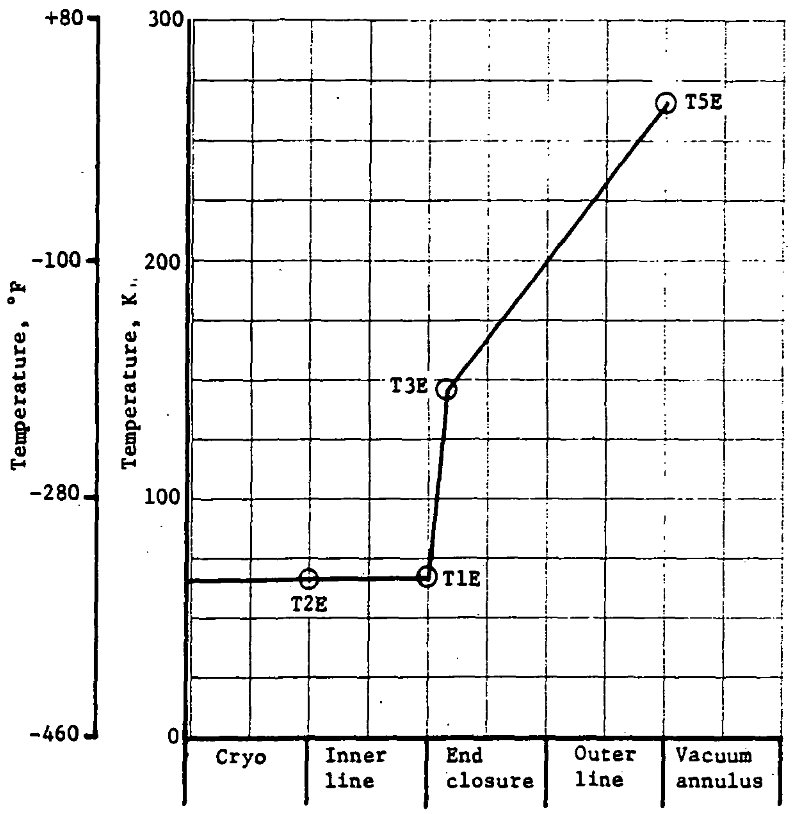


Figure 59. - Temperature Profile Radially Through End Closure of 46 cm (18 in.) Tube

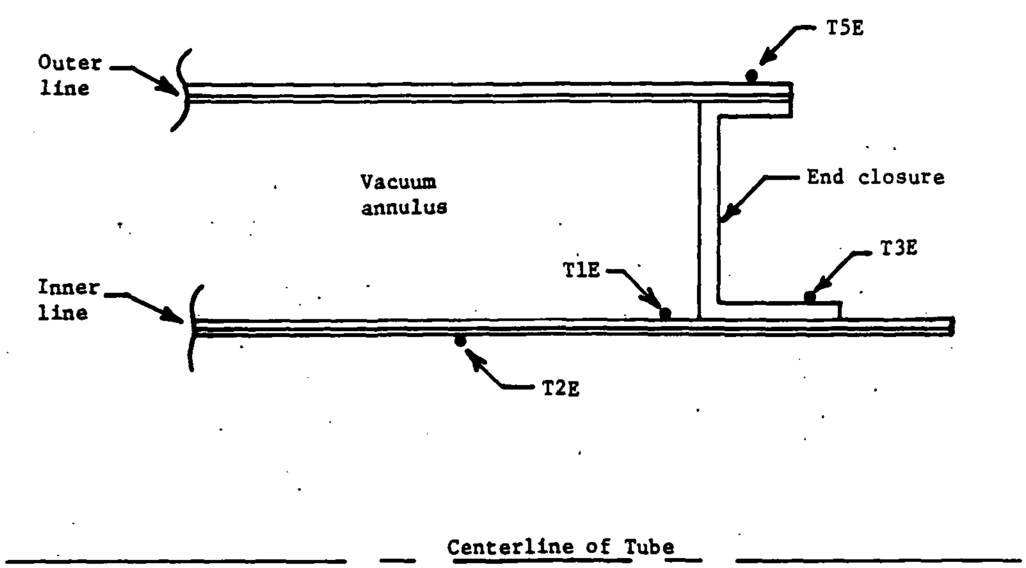


Figure 60. - Thermocouple Location for End Closure Temperature Distribution

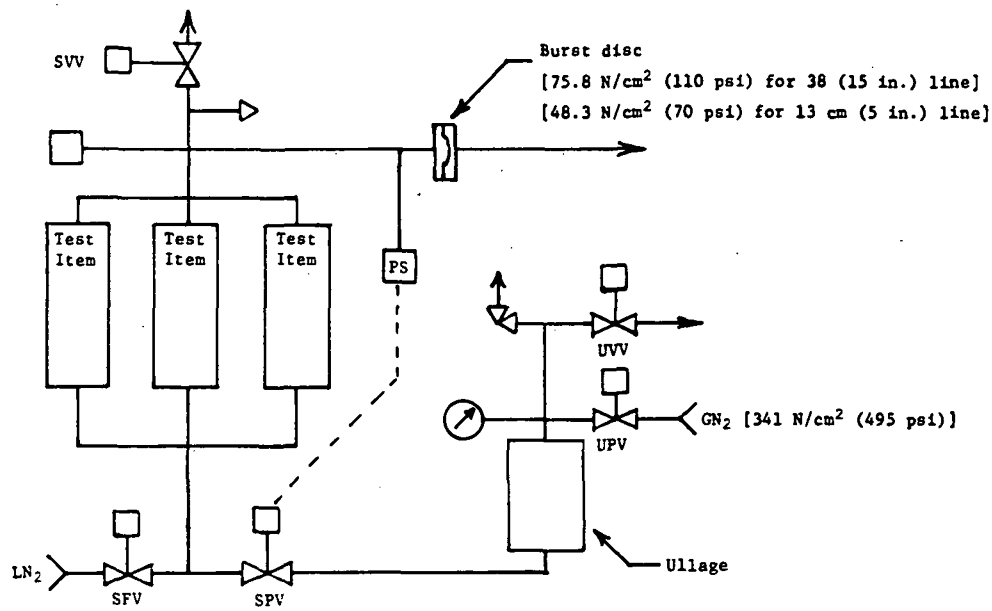


Figure 61. - Pressure Surge Cycle Test Fixture Schematic

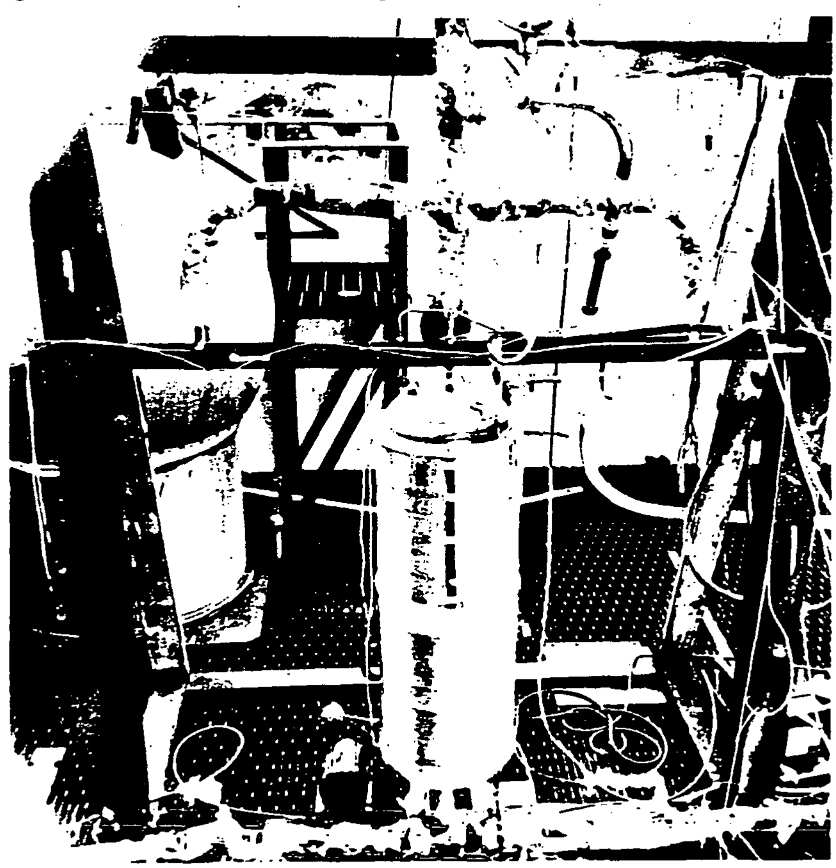


Figure 62. - Pressure Surge Test Setup

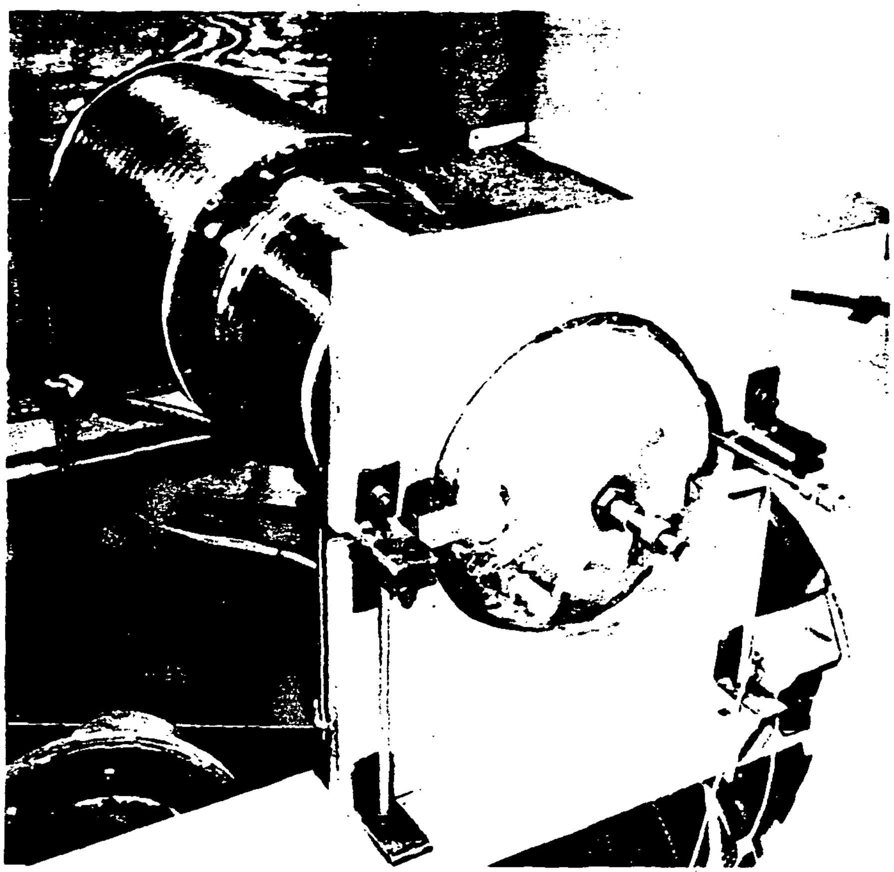


Figure 63. - A-B Tube Assembly Installed for Acoustic Test

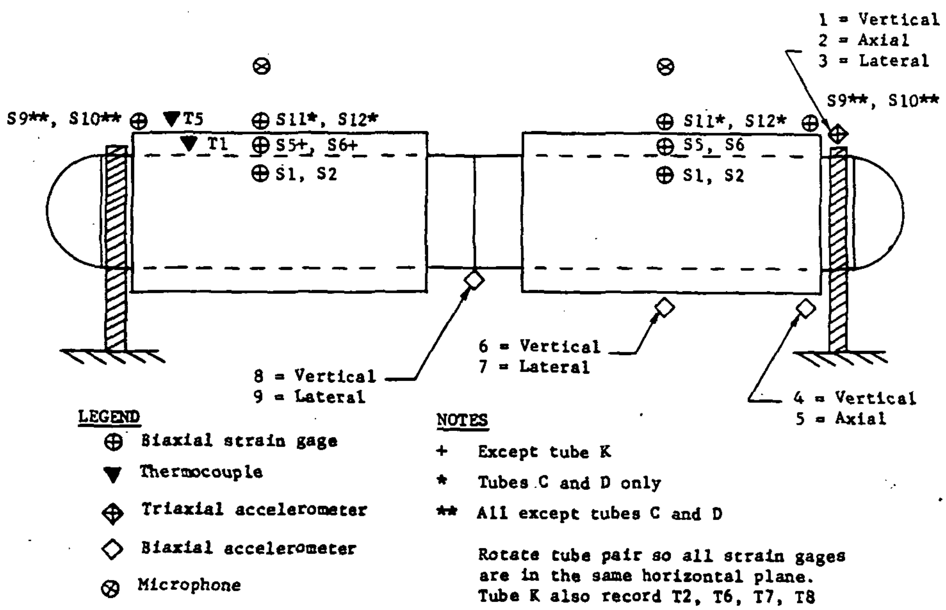


Figure 64. - Acoustic Test Instrumentation

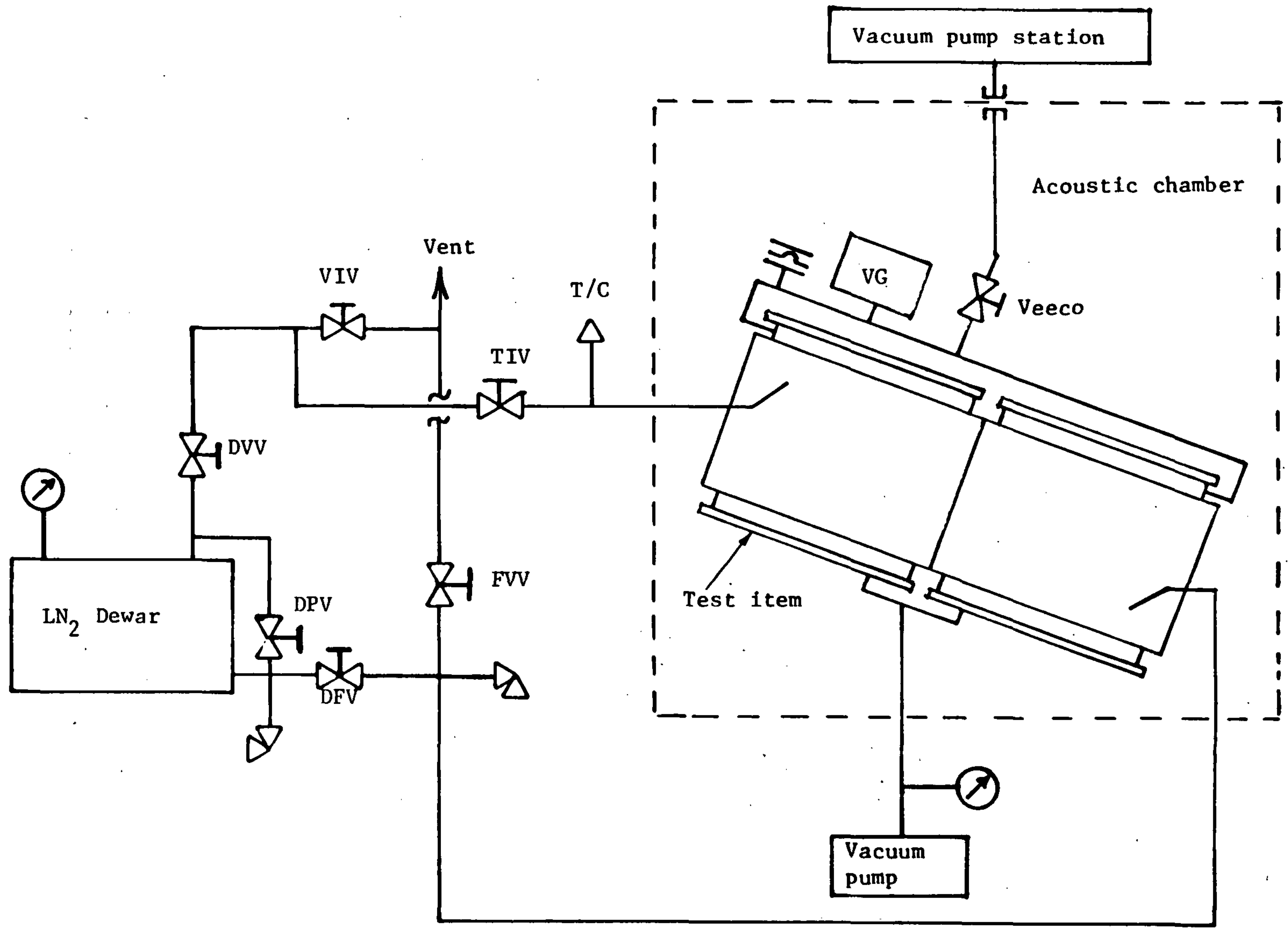


Figure 65. - Cryogenic Acoustic Test, Liquid Nitrogen Supply and Vent System

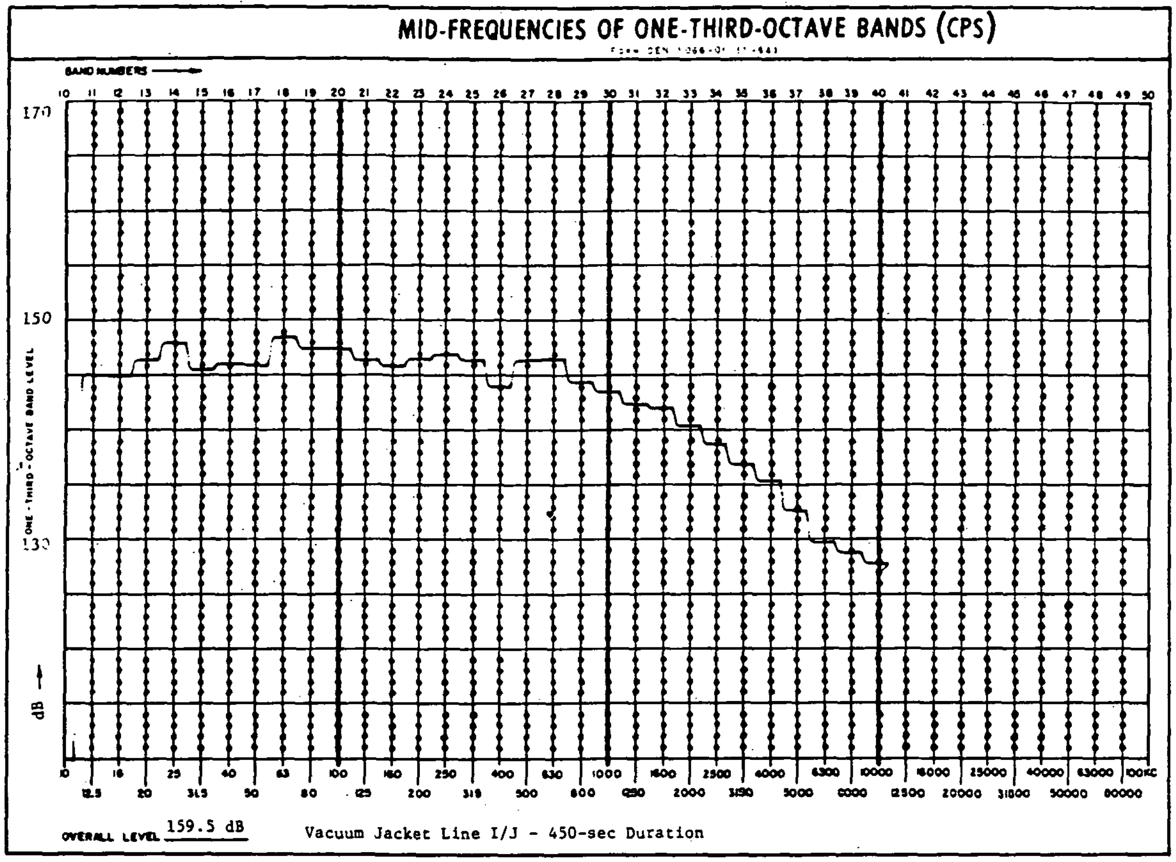


Figure 66. - Typical Input Spectrum (160 dB)

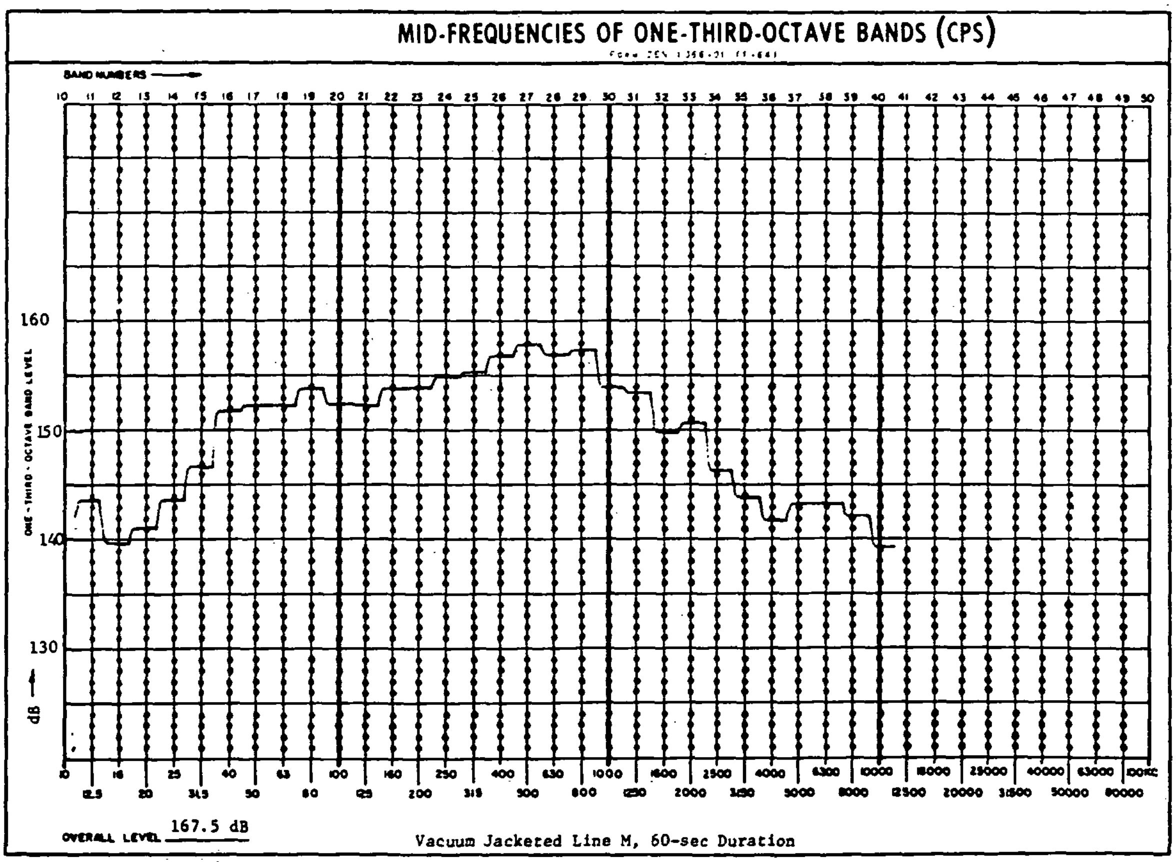


Figure 67. - Typical Input Spectrum (167 dB)

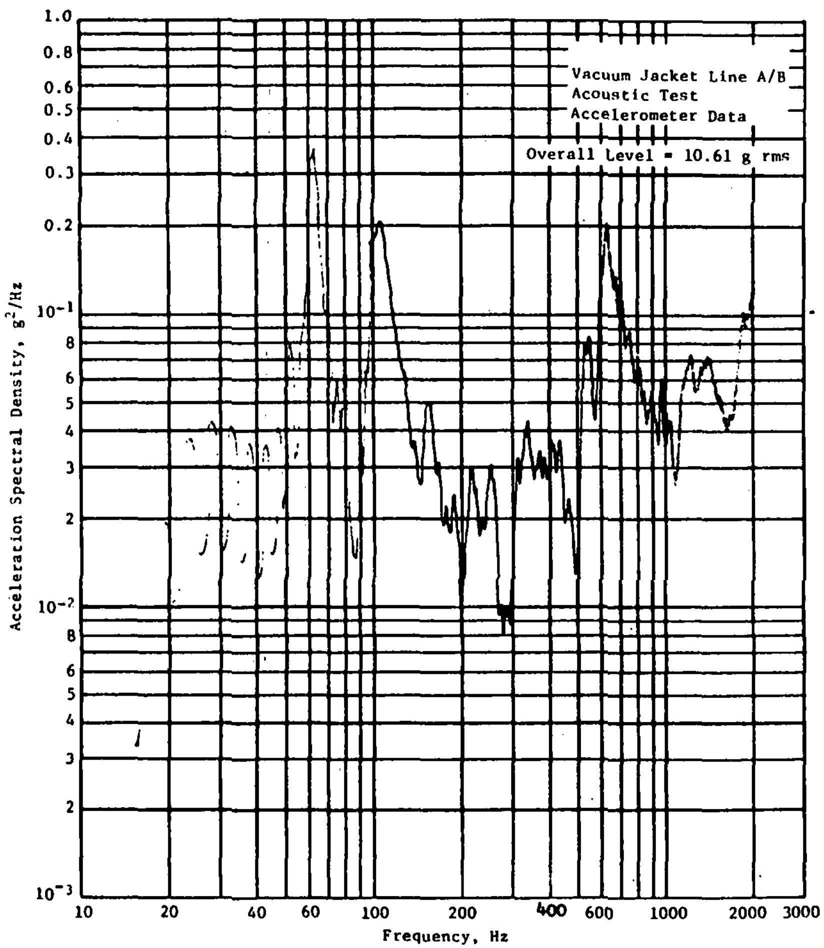


Figure 68. - Typical Acceleration Spectral Density Plot

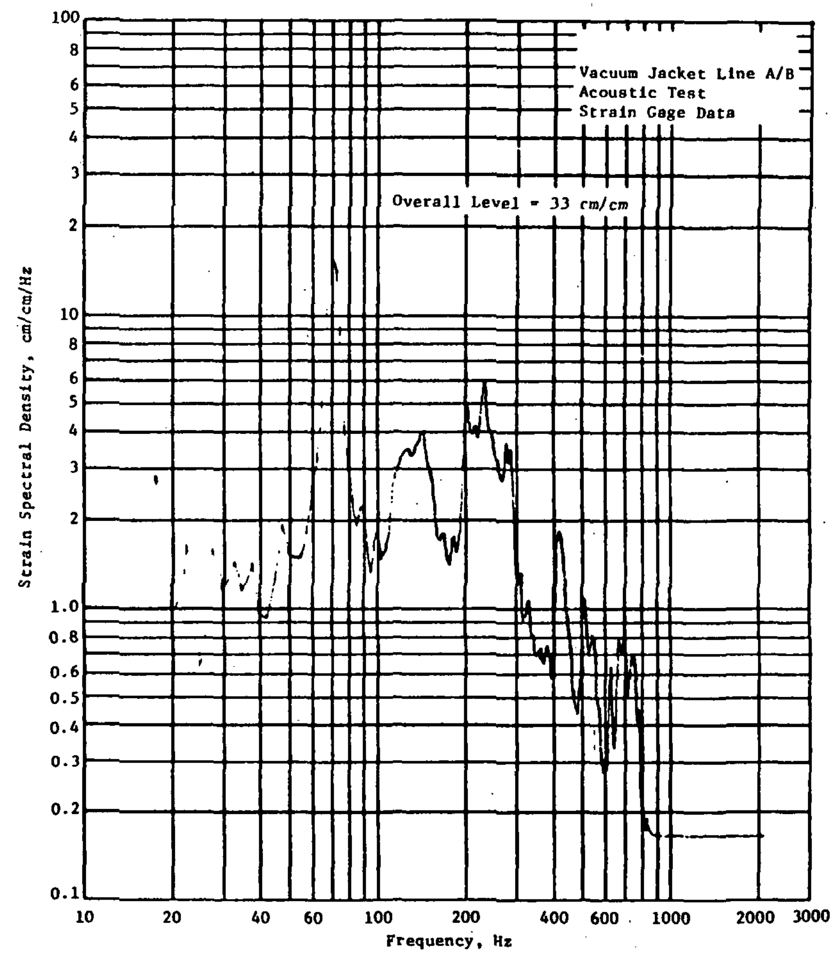


Figure 69. - Typical Strain Spectral Density Plot

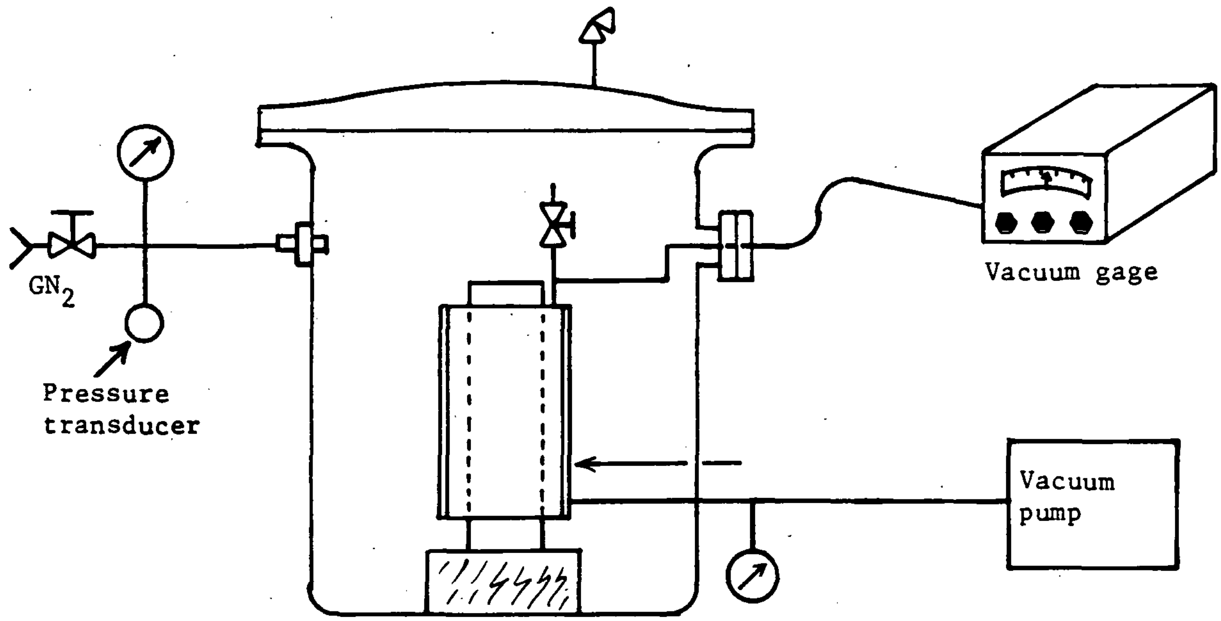


Figure 70. - External Collapse Test Setup Schematic

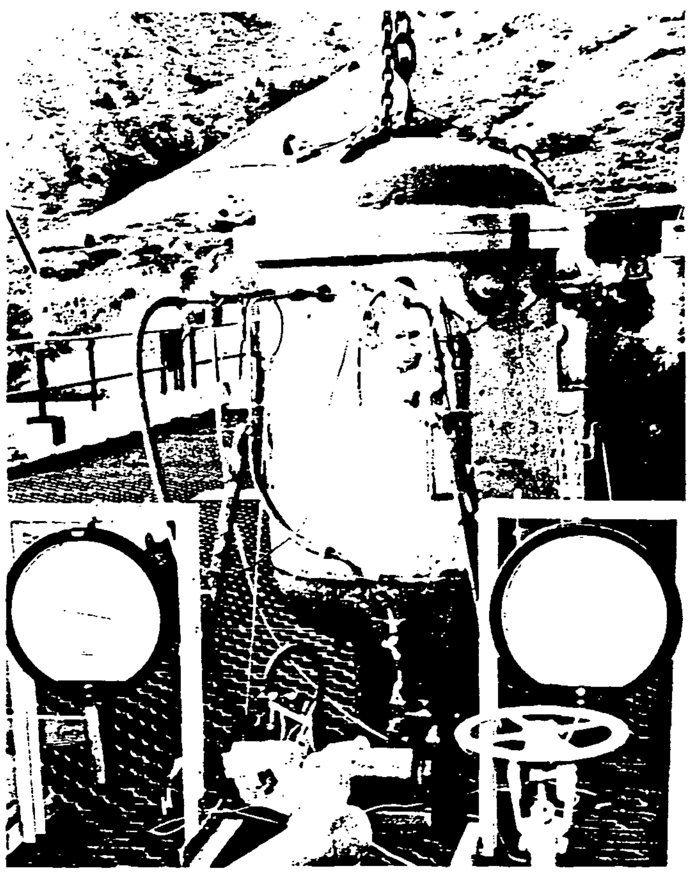


Figure 71. - External Collapse Test Chamber

Figure 72. - Tube C after External Collapse

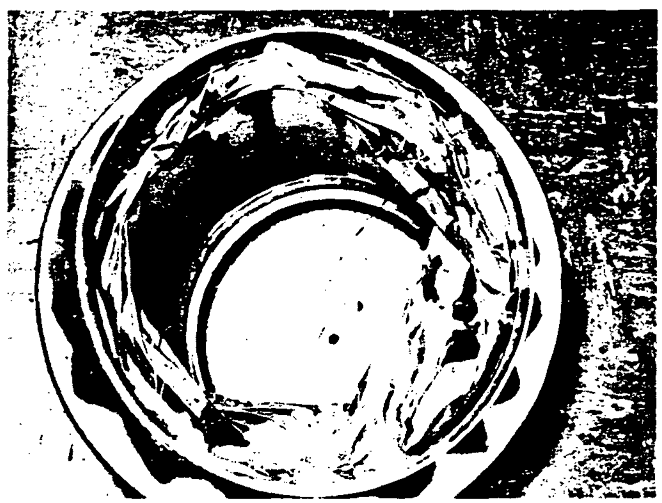


Figure 73. - Tube C after External Collapse (Inner Line)

ANALYSIS OF RESULTS

The design concepts for each major component in the test specimens produced during this program were analyzed and a recommended design was selected. The analysis included an evaluation of materials, producibility, performance, cost, and weight. A discussion of vacuum acquisition and vacuum maintenance is presented. The recommended designs consist of a composite vacuum jacketed line, which incorporates optimum components, and the tension membrane vacuum jacketed line. These designs are compared on the basis of weight with other existing state-of-the-art and advanced design concepts.

Analysis of Test Specimen Design Concepts. - The major components and design approaches used in the fabrication of the vacuum jacketed composite lines were evaluated. The evaluation considered each of the selected concepts and includes an analysis of the inner line, vacuum jacket, cost, weight, bonding, materials, end closures, standoffs, and vacuum acquisition and maintenance.

Inner line: The selected material for the commodity carrying inner lines was Inconel 718. Inconel 718 has a significant advantage over other corrosion resistant materials due to its high yield strength, 105,480 N/cm^2 (153,000 psi) achieved by heat treating. Because of the protection and damage resistance provided by composite overwrapping, thin gage materials are ideal for composite tubing. The wall thickness required with internal line pressures of 34 to 297 N/cm^2 (50 to 300 psi) for Inconel 718 and stainless steel 13 cm (5 in.) and 38 cm (15 in.) diameter lines are compared in Figure 74. The reduction in gage that can be achieved with Inconel 718 is clearly evident.

For small lines the minimum gage required for internal line pressure is often less than can be reliably produced. Liners of 0.008 cm (0.003 in.) thick were found to be very difficult to produce leak free. Three of the 13 cm (5 in.) diameter inner lines, however, were successfully made with 0.008 cm (0.003 in.) thick Inconel 718. All of these lines developed small wrinkles under the end fittings during composite curing, and one wrinkled badly during postcuring. No difficulty, however, was experienced in producing the 13 cm (5 in.) and 38 cm (15 in.) diameter test specimens with 0.013 cm (0.005 in.) Inconel 718.

Both fusion and resistance welding was used in the fabrication of the test specimens. Fusion welding the longitudinal tubing seam is more desirable in that it results in a smoother inner surface. The resistance welding requires a lap joint. The excess material is peeled away after welding but the result is a small ridge along the seam. Resistance welding, however, is more desirable for welding the end fittings. Fusion welding the end fittings results in a discontinuity in the line flow path due to the required weld preparation area. The flow path can be smooth if the end fittings are resistance welded to the thin lines. The differences in the two welding techniques are illustrated in Figure 75. Both welding techniques are acceptable for structural and zero leak criteria.

The inner lines were overwrapped with S/HTS glass fibers in a 58-68R resin system. The overwrap consisted of a layer of machine hoop wrapped 20 end roving, a half layer of longitudinally oriented glass cloth and a final layer of hoop wrap. The test specimens were overwrapped and cured while pressurized to preclude buckling. The overwrap and curing operations were performed with no anomalies. After initial curing, however, the inner lines were postcured at a temperature of 400°K (260°F) while in a vacuum of 0.0013 N/cm^2 (10^{-5} torr). The liners were not pressurized during postcure. One of the 0.008 cm (0.003 in.) liners buckled severely during postcure. To prevent buckling during high temperature postcure, internal pressurization is required.

Although not tested on this program, the use of PRD 49-III in the same 58-68R resin system should reduce the composite weight by the ratio of the material densities, 0.002 kg/cm^3 (0.085 lb/in.^{3}) for S-Glass and 0.001 kg/cm^3 (0.055 lb/in.^{3}) for PRD 49-III.

Early analysis (Appendix A) indicated that a structural bond between the overwrap and the thin metal liner is required for inner line axial load carrying capability. It was found, however, that bonding is not required for the inner line, because the delta pressure between the inner line and the vacuum jacket provides additional structural rigidity. Tests demonstrated an axial load capability in excess of 2268 kg (5000 lb) for unbonded 38 cm (15 in.) diameter lines.

Vacuum jacket: Test specimens were produced using five different vacuum jacket design concepts. The five design concepts are evaluated on the basis of producibility, cost, and weight. Of the composite vacuum jackets, the internal convolute design is superior because of producibility considerations. The tension membrane is a structurally sound, light-weight concept, but is the most expensive to produce. A discussion of the evaluation parameters is provided in the following paragraphs.

Vacuum jacket producibility: The three primary areas considered are thin metal liner fabrication, composite overwrap, and assembly. Metal liners were successfully produced in sizes of 20 and 46 cm (8 and 18 in.) diameter from 0.013 cm (0.005 in.) Inconel 718, which were leak free and did not wrinkle during the composite curing. One 20 cm (8 in.) diameter vacuum jacket liner was produced using 0.030 cm ((0.012 in.) Inconel 719. The heavier gage liner had fewer imperfections (tooling marks, etc.) than the thinner gage liners. The tension membrane vacuum jackets were successfully produced by hydrostatically bulge forming 0.046 cm (0.018 in.) thick cylinders and then chem-milling to the final thickness of 0.0191 cm (0.0075 in.). This fabrication technique proved very successful.

The 20 and 46 cm (8 and 18 in.) diameter vacuum jackets were overwrapped with two hoop layers of ±0.09 rad (±5 deg) crisscross wrapping. The overwrap material used was S-Glass preimpregnated with Epon 828-mpda resin. This process worked quite well. The ±0.09 rad (±5 deg) wrap pattern results in some build up of composite at the ends, which caused some difficulty with one 20 cm (8 in.) diameter vacuum jacket that had an internal convolute near the end for expansion and contraction purposes. The composite build up tended to roll over into the convolute and fill it. This, however, was easily corrected by locating the convolutes 2 cm (0.8 in.) from the ends.

Vacuum jackets with smooth metallic liners were the easiest to overwrap; vacuum jackets with external convolutes were the most difficult. The problem with the external convolutes is that the roving tends to slide off the convolute leaving minute areas of metal that are not covered. This problem can be eliminated by the use of wider roving or tape and/or by reducing the wrap tension.

The vacuum jackets were fusion welded to the inner lines after overwrap. The temperature of the composite was maintained below 367 K (200°F) during welding by flowing cold gaseous nitrogen through the tubes. Stainless steel tubes, 1.3 and 0.96 cm (0.5 and 0.38 in.) diameter, were welded into the vacuum jacket end closure to be used as vacuum acquisition ports and instrumentation feedthroughs. Even though temperature control was attempted during welding, composite disbonds developed in the vacuum jackets, and end closure warpage occurred because of the welding heat. It is recommended that future vacuum jackets use resistance welding to reduce heat, and that the vacuum ports be welded before assembly using welding techniques that will not warp the end closure flange. Bellows manufacturers have no difficulty in making these welds.

Vacuum jacketed composite line cost: The cost of the vacuum jacketed line assemblies for each of the five design concepts was compared during concept evaluation in Task I (Table IX). This data did not change as a result of the fabrication and test experience gained on this program. The unit costs are based on a production quantity of two each. The cost for producing each design concept for the composite vacuum jacketed lines is essentially equal. The cost for the tension membrane concept is greater than for the composite concepts.

Vacuum jacketed composite line weight: The weight of each of the composite design concepts was approximately equal. The weight of the composite designs is compared to the tension membrane design in Table XX. For weight evaluation the composite vacuum jacket liner material thickness was based on the thickness required to withstand an external pressure of 25 N/cm^2 (36.7 psi) without relying on the overwrap for structural support.

Bonding overwrap to vacuum jacket metal liners: All composite design concepts involved bonding the overwrap to 0.013 cm (0.005 in.) thick Inconel 718 liners to reduce weight. This concept proved unsuccessful in that the bond did not develop sufficient strength to resist loading in peel. (See Appendix D for a thorough discussion of bonding failures.) Current state-of-the-art bonding techniques are inadequate for this application. Thus, it is essential that the vacuum jacket metal liners be of sufficient strength to withstand external pressure loading without relying on the overwrap. The overwrap, however, is still required to provide handling and damage resistance if minimum weight is required. A nonoverwrapped vacuum jacket of minimum gage (for external pressure) is very susceptible to damage and not acceptable for flight. The addition of the overwrap provides the required damage resistance with less added weight than would result from increasing metal line thickness.

Vacuum jacket liner material: Due to the external pressure (buckling loading) the vacuum jacket liner thickness is a function of material modulus and not yield strength. Thus Inconel 718 has no advantages over stainless steel for the jacket liners. Stainless steel is the preferred material because it is less expensive and has superior forming and welding characteristics.

The liner thickness is minimized by convolutes that provide resistance to buckling. The required liner thickness for stainless steel vacuum jackets is plotted as a function of diameter in Figure 76.

TABLE XX. - WEIGHT COMPARISON, COMPOSITE VERSUS TENSION MEMBRANE VACUUM JACKETED LINES

Inner line diameter, cm (in.)	60.96 cm (24 in.) long line		609.6 cm (240 in.) long line	
	Composite kg (lb)	Tension membrane kg (lb)	Composite kg (lb)	Tension membrane kg (lb)
13 (5)	3.4 (7.4)	--	22.2 (49.1)	--
25 (10)	6.7 (14.8)	--	41.9 (92.7)	--
38 (15)	10.1 (22.2)	9.2 (20.2)	62.7 (138.5)	49.2 (108.6)
51 (20)	13.4 (29.5)	--	81.4 (179.8)	--

Design Assumptions:

1. Composite vacuum jacket metal gage = 0.03 cm (0.012 in.) for 13 cm (5 in.) diameter
   Composite vacuum jacket metal gage = 0.036 cm (0.014 in.) for 25 cm (10 in.) diameter
   Composite vacuum jacket metal gage = 0.041 cm (0.016 in.) for 38 cm (15 in.) diameter
   Composite vacuum jacket metal gage = 0.046 cm (0.018 in.) for 51 cm (20 in.) diameter

2. Composite vacuum jacket overwrap gage = 0.041 cm (0.016 in.) S-Glass for all diameters.

3. Composite inner line metal gage = 0.013 cm (0.005 in.) Inconel 718 for all diameters.

4. Composite inner line overwrap gage = 0.051 cm (0.020 in.) S-Glass for all diameters.

5. Vacuum annulus spacing = 3.81 cm (1.5 in.) for all diameters.

6. Tension membrane metal gage = 0.019 cm (0.0075 in.) in the chem-milled areas.

7. Vacuum jacket metal gage is based on an external pressure loading of 25 N/cm^2 (36.7 psi) or 2.5 times atmospheric pressure.

End closures: The end closure design used for all composite vacuum jacket test specimens consisted of a 0.109 cm (0.043 in.) channel shaped ring. This configuration was designed to transfer all axial pressure loading to the inner line and to transfer the inner line thermal contraction to the vacuum jacket. The vacuum jacket was then convoluted to accommodate the inner line thermal contraction. This design concept proved successful but is not optimum for minimum weight or thermal heat leak.

Convair's analysis (ref 4), was used as a basis for selecting a low weight thermally efficient end closure for incorporation into the composite vacuum jacketed design. The design, as shown in Figure 77, features a bellows section welded to both inner line and vacuum jacket. The bellows is 0.013 cm (0.005 in.) thick stainless steel and provides a tortuous heat leak path. This design, because of the bellows section, does not require that the vacuum jacket be convoluted for expansion and contraction. A disadvantage to this design is that a standoff support is required near the end closure because the bellows is not designed to withstand loading normal to the axis of the line.

Standoffs: A composite I-section standoff was used in each of the 46 cm (18 in.) composite vacuum jackets. This design was difficult to install and was not optimized for minimum weight or heat leak. The standoff support pad consisted of a composite ring stiffener overwrapped on the inner line. Tolerance control on the support pad proved to be difficult, which contributed to the installation problems. Thus, the composite I-section concept is not recommended for future application. Convair, in their vacuum jacketed line technology investigation (ref 4), performed an evaluation of state-of-the-art standoff designs. The design shown in Figure 77 proved to be optimum for minimum weight and heat leak considerations. This design was used on the S-II LH_2 vent line and is adaptable for use in composite vacuum jacketed lines.

Vacuum acquisition and maintenance: During this program the vacuum acquisition and maintenance objectives were met using tube M. The minimum annulus pressure obtainable was 6×10^{-4} torr and the vacuum decay rate was 2.6 μ/day over an 81-day period. The principles of vacuum engineering were used as applicable. A discussion of these principles and the various factors which must be considered to obtain and maintain vacuum at the required levels follows.

Materials of construction must be carefully selected because every material, when exposed to vacuum conditions, will liberate gas to varying degrees by outgassing. Outgassing includes evaporation, adsorption, absorption, chemisorbtion molecules in solution, and molecules from decomposition of materials. In addition to outgassing, diffusion, permeation, trapped volumes and porous leaks are undesirable material characteristics. In general, materials of closed cell construction with smooth clean surfaces are better in this regard. Stainless steel is the most popular construction material. But Inconel, aluminum, brass, and iron are equally acceptable.

Construction techniques should eliminate all possible leak paths by welding all joints. Threaded seals such as pipe threads should not be used. The geometry of the vacuum space should be such that volumes are interconnected by large passage ways, and valves and tubes leading to the vacuum space should have as large an internal diameter as possible. Static seals should be metal bellows if possible.

Before the components are assembled, they should be thoroughly cleaned by vapor degreasing or by the use of a highly volatile solvent to remove oil and other contaminants. Low vapor pressure and volatility are of prime importance in solvent selection.

Assembly of the components should be by 100% gas shielded arc welding to eliminate flux outgassing. After welding, a helium mass spectrometer leak check should be made and any leaks should be repaired.

It is imperative that the annulus be leak free to achieve a pressure rise rate of less than 5 μ/day. Using the ideal gas law, a 5 μ/day pressure rise can be translated into an allowable leakage rate for a given annulus volume. For a 38 cm (15 in.) diameter inner line with a 46 cm (18 in.) diameter vacuum jacket, 305 cm (120 in.) long, the leak rate equivalent to a 5-μ/day pressure rise is calculated as:

$$PV = WRT$$

$$W = \frac{PV}{RT}$$

$$\Delta W = \frac{\Delta PV}{RT}$$

$$\Delta W = \frac{(15 - 10)(152.9)}{(21{,}600)(300°K)} = 1.18 \times 10^{-5} \text{ kg/day } (2.61 \times 10^{-6} \text{ lb/day})$$

1.18×10^{-5} kg/day is equivalent to 1.14×10^{-5} scc/sec.

The allowable gas load of 1.14×10^{-5} scc/sec consists of leaks, outgassing and permeation. Outgassing can be reduced to insignificant magnitudes by proper bakeout. The equivalent leak rate attributable to outgassing is calculate as 4.8×10^{-10} scc/sec using the methods of reference 5. A leak of 1.14×10^{-5} scc/sec is, therefore, allowed and for reference purposes the size of the hole which would cause this leak can be calculated using Knudsen's Law for molecular flow and the techniques of reference 6.

$$Q = \frac{20.48\ r^3}{L}\sqrt{\frac{T}{M}}\,(P_1 - P_2)$$

$$r = \left(\frac{QL\sqrt{M}}{20.48\sqrt{T}\ \Delta P}\right)^{1/3}$$

$$r = \left(\frac{8.64 \times 10^{-3} \times 0.0305 \times 29}{20.48 \times 293 \times 759{,}900}\right)^{1/3}$$

$$r = 1.52 \times 10^{-4}\ \text{cm}\ (6 \times 10^{-5}\ \text{in.})$$

In conclusion, it is seen that a vacuum decay rate of 5 μ/day is equivalent to a leak of 1.14×10^{-5} scc/sec or a single leak path diameter of 0.0003 cm (0.00012 in.).

Vacuum acquisition of the vacuum annulus begins after assembly and usually consists of bakeout and pumping operations. The bakeout is usually required to provide activation energy to release the trapped molecules (sorbed, dissolved, etc) and the pumping is required to remove these molecules. The configuration of the ideal vacuum acquisition system is a large capacity, low pressure pump, short-coupled to the vacuum annulus. In the molecular regime, flow in a tube is dependent on rebound in the desired direction; and is proportional to the diameter cubed and inversely proportional to the length. In the more familiar viscous regime, flow is caused by differential pressure forces and is proportional to the diameter squared and inversely proportional to the length. Therefore, in vacuum work, the diameter of the flow passages is much more critical than in conventional fluid flow.

Vacuum maintenance is not necessarily limited to continuous evacuation but also refers to the rate of annulus pressure increase when the annulus is isolated. The vacuum maintenance requirement for aerospace use is generally 5 μ/day in the range of 10 to 100 μ Hg. Good vacuum maintenance is directly dependent upon the quality of the previous steps (design and fabrication).

Nonmetallics in the vacuum annulus increase the difficulty of acquiring and maintaining a hard vacuum. These difficulties can be overcome by proper cleaning and bakeout procedures as was demonstrated by the vacuum maintenance testing performed on the M-test specimen, which had a composite overwrap on the inner line. An additional fabrication step may be employed, however, which should make the composite vacuum jacketed line equivalent to all-metal lines for vacuum integrity. A thin coating of aluminum applied by vacuum deposition over the composite would entrap any outgassing constituents. There would then be a zero delta pressure across the aluminum coating when the annulus is evacuated, thus eliminating any outgassing from the composite overwrap. This process requires development to determine the required coating thickness and application techniques for leak free sealing, but is considered well within the state-of-the-art of existing equipment capability. The aluminum coating has an added benefit in that it provides a radiation shield over the composite and may eliminate the requirement for a layer of aluminized mylar required for thermal efficiency.

Recommended Design, Vacuum Jacketed Composite Lines.- Based on the results of this program, the recommended vacuum jacketed composite line is depicted in Figure 78. The design, featuring the optimum inner line, vacuum jacket, and detail components discussed previously, is based on a 35.6 cm (14 in.) diameter by 304.8 cm (120 in.) long line for a direct comparison with current state-of-the-art designs and an advanced state-of-the-art vacuum jacketed line. A discussion of the specific design details follows.

The inner line consists of 0.013 cm (0.005 in.) thick Inconel 718 liner overwrapped with S-Glass fibers 0.05 cm (0.020 in.) thick preimpregnated with a 58-68R resin system. The liner has a single longitudinal fusion weld with resistance welded end fittings. The end fittings are stainless steel.

The vacuum jacket is 0.038 cm (0.015 in.) thick 304 stainless steel with 0.51 cm (0.2 in.) radius internal convolutes spaced at 3.8 cm (1.5 in.) intervals. The convolutes are filled with a low density foam machined to the outside diameter of the vacuum jacket liner. The vacuum jacket liner is overwrapped with S-Glass fibers 0.05 cm (0.020 in.) thick preimpregnated with Epon 828-mpda resin.

The vacuum end closures feature a stiff design at one end of the line and a flexible bellows at the other end. The stiff end closure is resistance welded to the vacuum jacket liner and either fusion or resistance welded to the inner line end fitting. Vacuum components consisting of vacuum acquisition valve, vacuum gage, burst disc, and inner line instrumentation port are installed in the end closure. The flexible bellows type end closure is fusion welded to both the inner line and the vacuum jacket and allows the inner line to expand and contract without transferring axial load into the vacuum jacket.

The standoffs are spaced at 60.4 cm (24 in.) intervals and consist of 12-sided teflon rings that are slipped over the inner duct and retained in place by 0.153 cm (0.06 in.) L-brackets on each side.

State-of-the-Art and Advanced Vacuum Jacketed Line Designs.- The Convair Aerospace Division, in their Vacuum Jacketed Ducting Technology Investigation (ref. 4), performed an analysis of existing state-of-the-art vacuum jacket designs. These designs are depicted in Figure 79 and described in the following paragraphs. All designs were scaled-up to a typical common 35.6 cm (14 in.) inner line diameter. The inner line material is 321 stainless steel of 0.152 cm (0.06 in.) wall thickness. The vacuum jackets are designed for an external pressure loading of 25 N/cm^2 (36.7 psi).

Design 1 - S-IVB Main LH_2 Supply Duct (Obsolete): A 1.587 cm (0.625 in.) vacuum cavity filled with glass-fiber of 64.08 kg/m^3 (4.0 lb/ft^3) density is enclosed by an 0.040 cm (0.016 in.) 321 stainless steel shell. This shell has 1.27 cm (0.5 in.) high convolutions on 2.54 cm (1.0 in.) centers to provide longitudinal expansion and contraction. The convolutions also provide support for externally applied loads.

Design 2 - S-IVB and S-II Main LH_2 Supply Ducts (Current Design): A 0.723 cm (0.285 in.) vacuum cavity is enclosed by a 0.051 cm (0.020 in.) 321 stainless steel shell. This shell has 0.553 cm (0.218 in.) high square convolutions, 2.8 cm (1.10 in.) wide on 2.8 cm (1.10 in.) centers.

Design 3 - Centaur LH_2 Supply Duct: A 1.905 cm (0.75 in.) thick Freon blown polyurethane foam of 64.08 kg/m^3 (4.0 lb/ft^3) is the basic insulation. Approximately 30% of the foam is removed by scalloping. The foam is covered by a five layer blanket-type aluminized Mylar/Dacron radiation shield.

Design 4 - S-IVB LH_2 Recirculation Line: A 1.27 cm (0.5 in.) vacuum cavity is enclosed by an 0.356 cm (0.14 in.) 321 stainless steel straight shell. The inner duct is wrapped with two alternate layers of 0.005 cm (0.002 in.) aluminum foil and 0.02 cm (0.008 in.) Dexter paper.

Design 5 - S-II LH_2 Vent Line: A 1.27 cm (0.5 in.) vacuum cavity is enclosed by a 0.254 cm (0.10 in.) 321 stainless steel shell. The shell has 0.965 cm (0.38 in.) high convolutions on 11.43 cm (4.5 in.) centers.

Convair's parametric evaluation shows Design 4 having the highest performance rating based primarily on excellent thermal performance and reliability.

In addition, Convair performed an evaluation of advanced vacuum jacketed line design concepts. A design concept which promised the most favorable performance characteristics, was selected for design fabrication and test. The design consists of a straight section of vacuum jacketed duct 35.6 cm (14 in.) diameter by 305 cm (120 in.) long (Fig. 80). The Standoffs are located 76 cm (30 in.) from each end and consist of eight 0.64 cm (0.25 in.) radial tubes welded to the inner line.

The outer vacuum jacket consists of a stainless steel inner shell 0.064 cm (0.025 in.) thick with a fiberglass honeycomb material (Hexcel HRHIO-OX-3/16-3.0) which is an overexpanded, flexible honeycomb. Attachment of components to the jacket is made by means of an end fitting as shown in Figure 80. The vacuum jacket end closures consist of a bellows nested within the outer jacket.

The description of these designs is included here to provide data for weight comparison with the composites and tension membrane vacuum jacketed designs.

Tension Membrane Vacuum Jacketed Line. - The tension membrane vacuum jacketed line as depicted in Figure 7, is scaled to a 36 cm (14 in.) diameter, 305 cm (120 in.) long line for a direct weight comparison with other design concepts. The design features a composite inner line and standoffs on 61 cm (24 in.) centers identical to that shown in Figure 78. The tension membrane is 0.0191 cm (0.0075 in.) thick stainless steel having a minor diameter of 38 cm (15 in.) and a major diameter of 43 cm (17 in.) with a bay length of 10 cm (4 in.). Each bay is supported by an aluminum hoop ring.

Weight Comparison of Vacuum Jacketed Design Concepts. - The recommended composite and tension membrane vacuum jacketed lines are compared on the basis of weight with the state-of-the-art designs and advanced design concepts defined in the preceding paragraphs. The weight comparison is based on a 36 cm (14 in.) diameter 305 cm (120 in.) long line for each design concept.

A comparison of the weights of the different design concepts is provided in Table XXI. The tension membrane concept is the lightest with the composite vacuum jacketed line concept next. behind. A major contribution to the weight of the state-of-the-art and the advanced designs is the inner line. The gage of the inner line could probably be reduced to about 0.102 cm (0.040 in.), which would save approximately 15.1 kg (33 lb) for these concepts. The inner line weight for these designs, however, is still significantly heavier than the composite inner line weight.

TABLE XXI. - WEIGHT COMPARISON, 36 cm (14 in.) DIAMETER, 305 cm (120 in.) LONG VACUUM JACKETED LINES

Design Concept	Component weight, kg (lb)							
	A	B	C	D	E	F	G	H
Inner line liner	3.4 (7.5)	3.4 (7.5)	41.6 (91.8)	41.6 (91.8)	41.6 (91.8)	41.6 (91.8)	41.6 (91.8)	41.6 (91.8)
Inner line overwrap	4.0 (8.7)	4.0 (8.7)	--	--	--	--	--	--
Inner line end fittings	1.3 (2.9)	1.3 (2.9)	--	--	--	--	--	--
Vacuum jacket liner	13.9 (30.6)	6.6 (14.6)	23.2 (50.7)	17.4 (37.9)	--	101.9 (221.9)	79.7 (173.6)	18.3 (40.3)
Vacuum jacket overwrap	4.2 (9.2)	--	--	--	--	--	--	--
Vacuum jacket honeycomb cover	--	--	--	--	--	--	--	9.7 (21.4)
Foam insulation	--	--	--	--	3.9 (8.6)	--	--	--
Vacuum jacket end closure	0.4 (0.9)	--				0.8 (1.7)		
Standoffs	2.3 (5.0)	2.3 (5.0)	1.1 (2.4)	1.1 (2.4)	--	1.1 (2.4)	1.1 (2.4)	1.1 (2.4)
Tension membrane support rings	--	6.6 (14.6)	--	--	--	--	--	--
Bellows for expansion/ contraction	1.1 (2.4)	--	0.5 (1.2)	0.5 (1.2)	--	0.5 (1.2)	0.5 (1.2)	2.1 (4.7)
Total	30.8 (67.2)	24.1 (53.3)	67.1 (146.1)	61.2 (133.3)	46.1 (100.4)	146.4 (319.0)	123.5 (269.0)	72.8 (160.6)

Design concepts:

A - Recommended composite vacuum jacketed line, Figure 78.
B - Tension membrane vacuum jacketed line, Figure 7.
C - SOA Design 1 - S-IVB main LH_2 supply duct (obsolete) Figure 79.
D - SOA Design 2 - S-IVB and S-II main LH_2 supply ducts, Figure 79.
E - SOA Design 3 - Centaur LH_2 supply duct, Figure 79.
F - SOA Design 4 - S-IVB LH_2 recirculation line, Figure 79.
G - SOA Design 5 - S-II LH_2 vent line, Figure 79.
H - Advanced design, Figure 80.

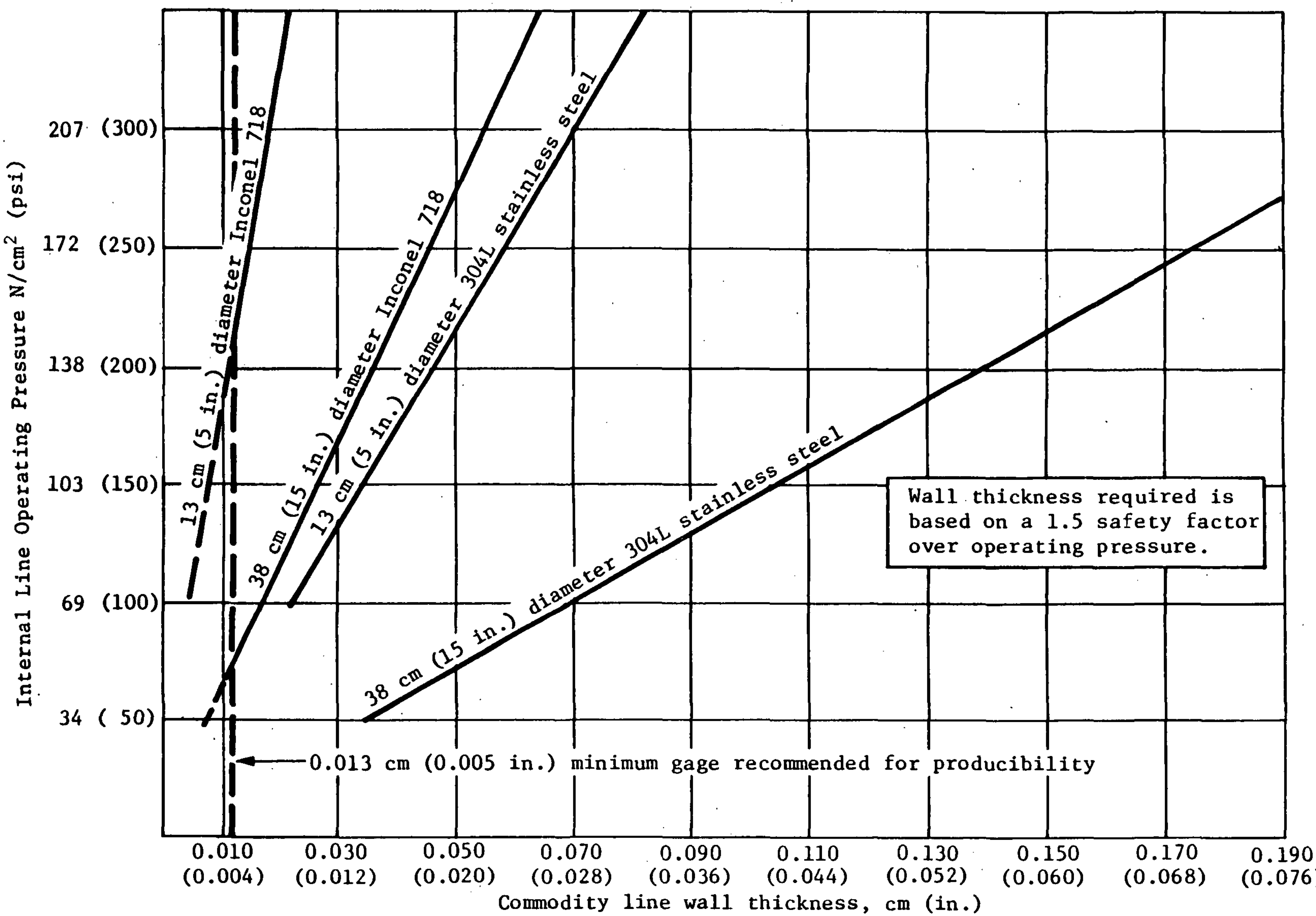


Figure 74. - Wall Thickness Comparison for Inconel 718 and Stainless Steel Tubes

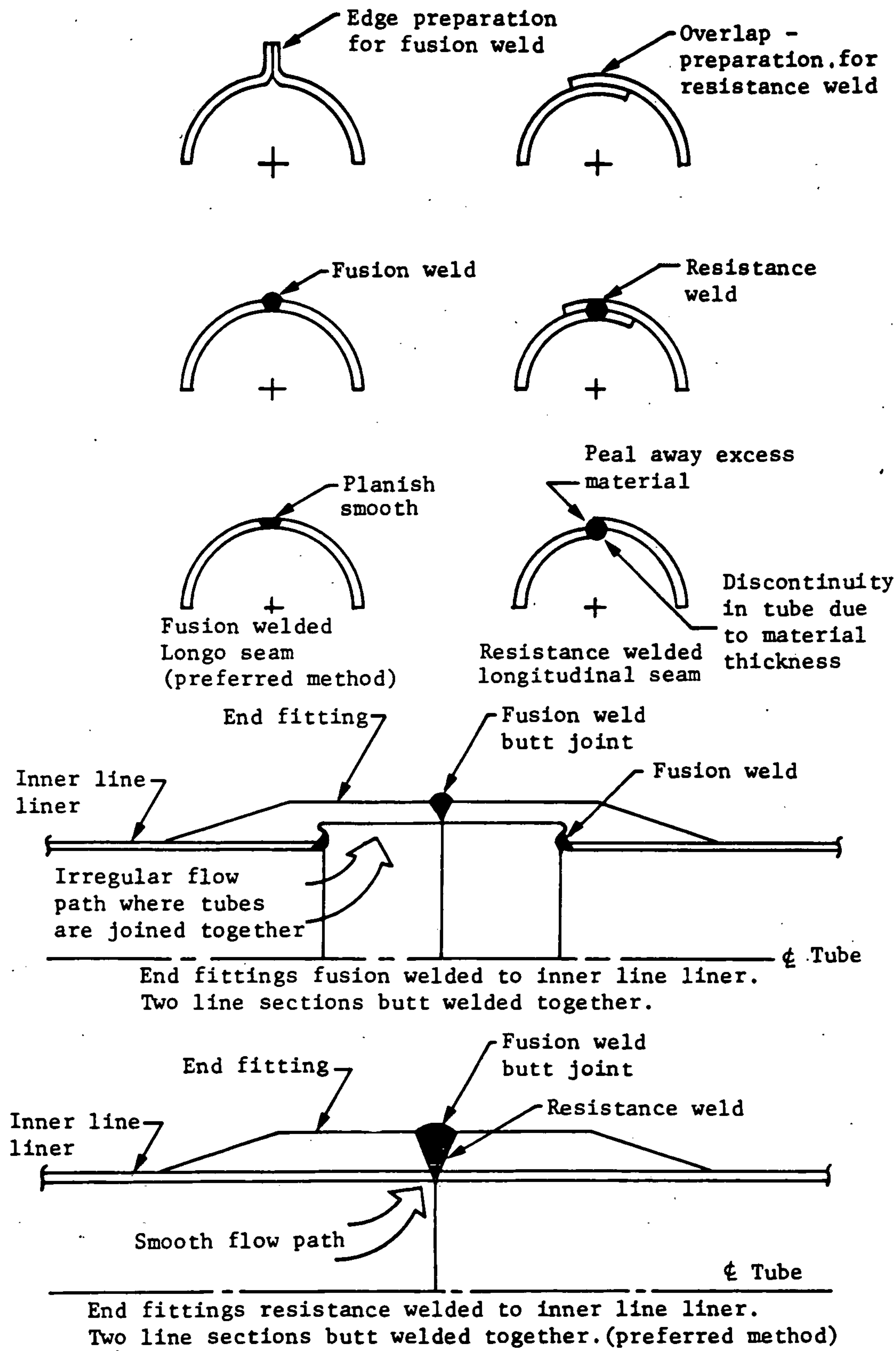
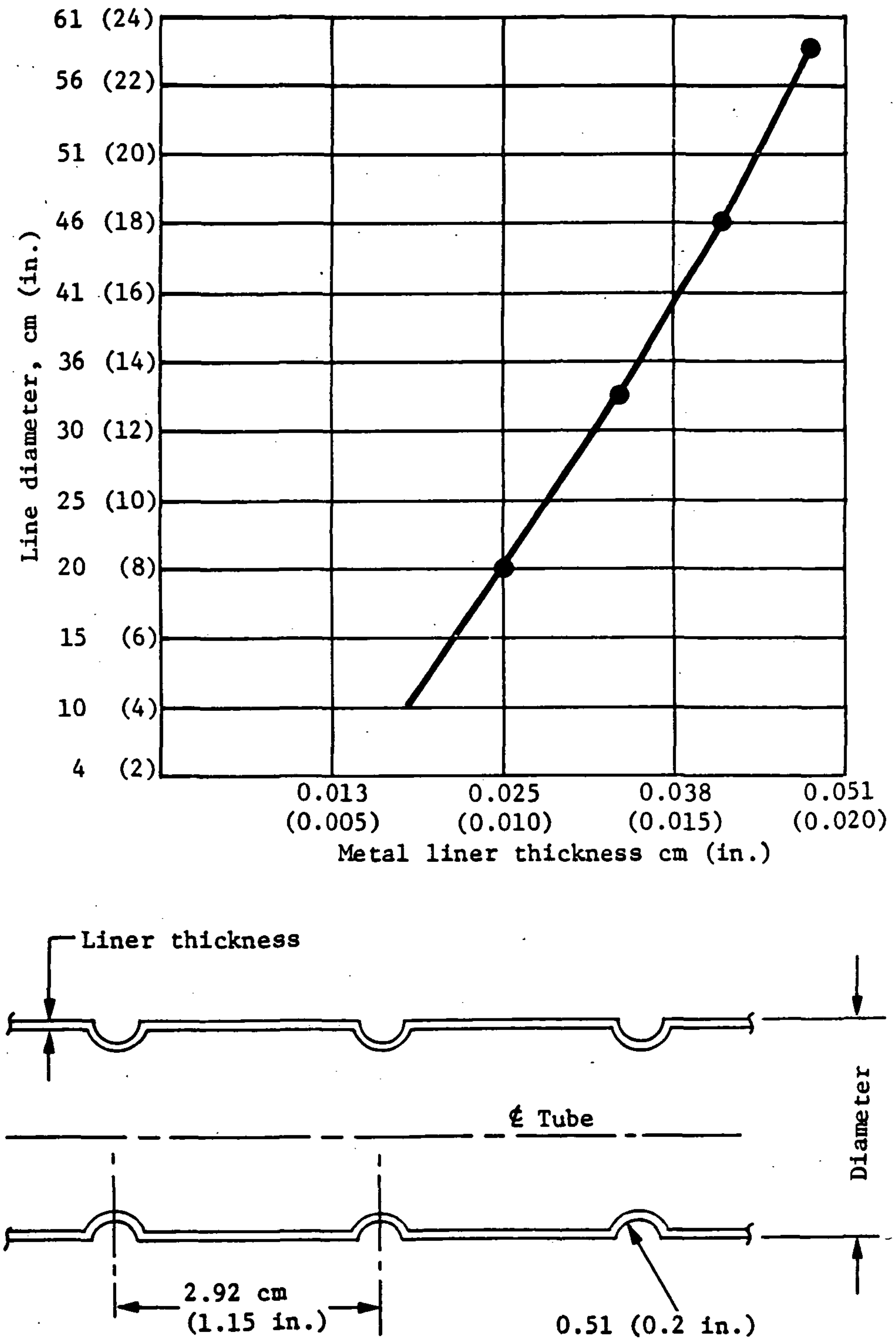


Figure 75. - Comparison of Fusion and Resistance Welding Techniques for Inner Line Fabrication



Material: 304 stainless steel
External pressure: 25 N/cm^2 (36.7 psid)

Figure 76. - Required Vacuum Jacket Liner Thickness Versus Diameter

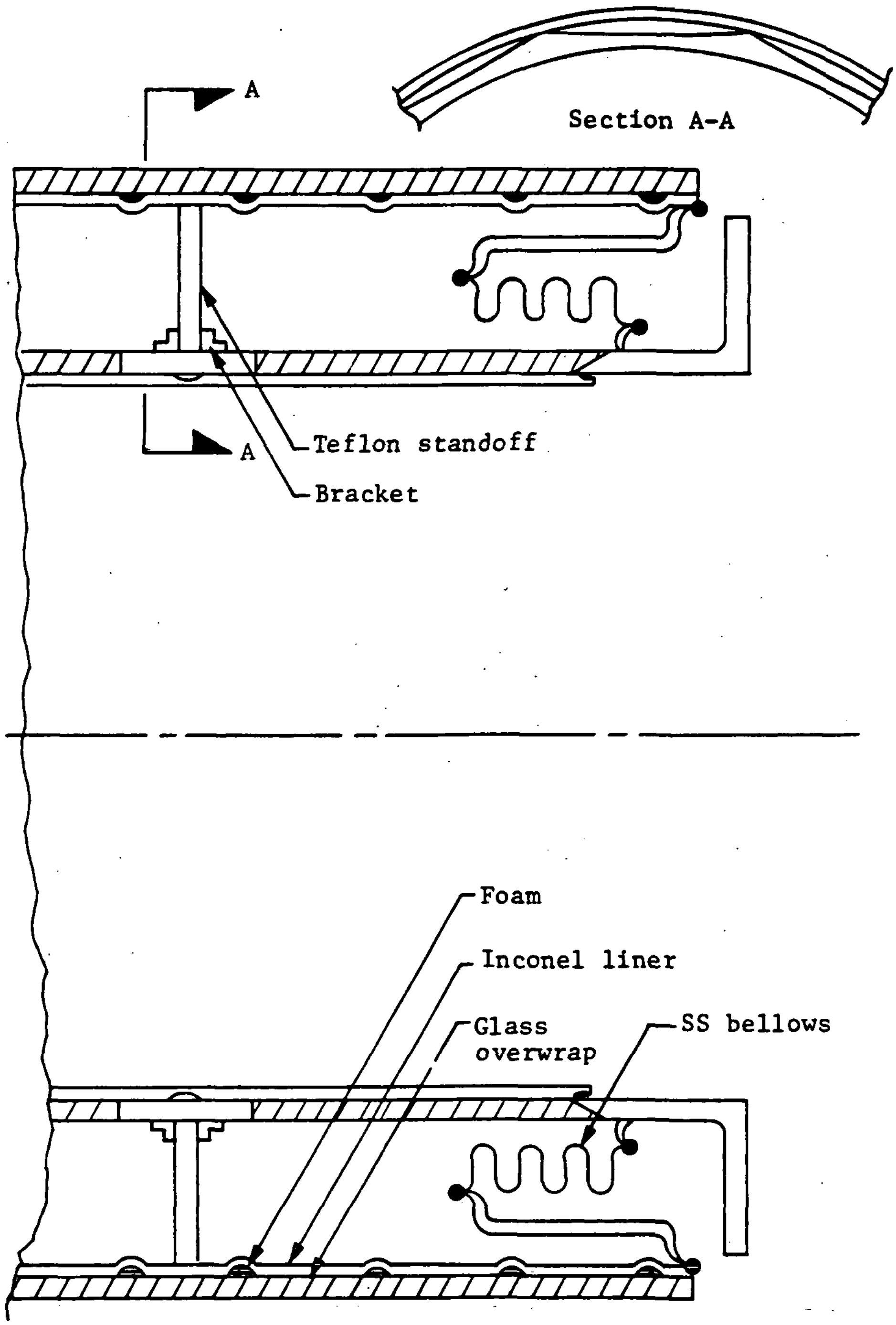
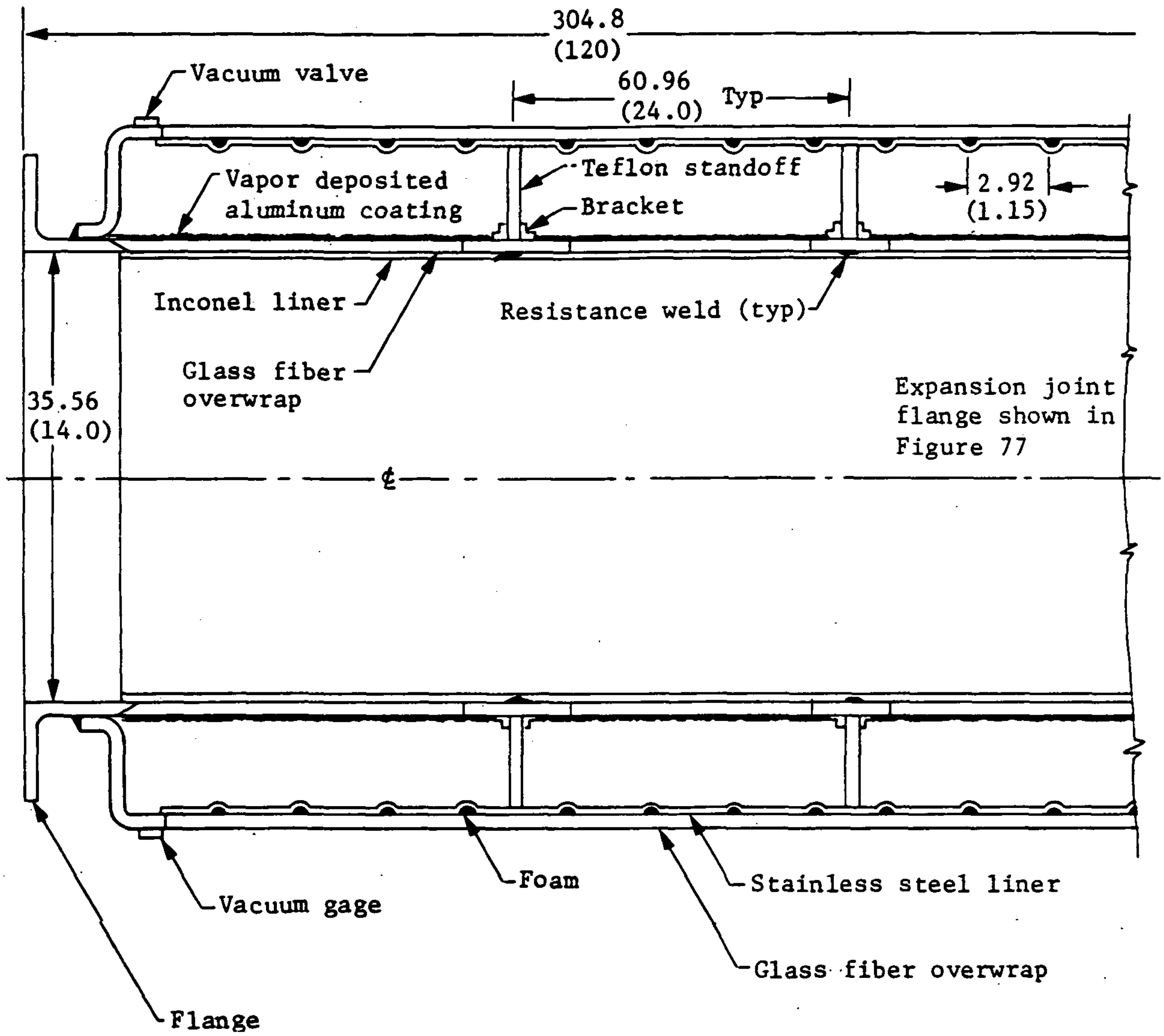


Figure 77. - Recommended Vacuum Jacketed End Closure and Standoff



All dimensions in cm (in.). Dimensions are shown for comparison with other design concepts of the same size.

Figure 78. - Recommended Vacuum Jacketed Composite Line

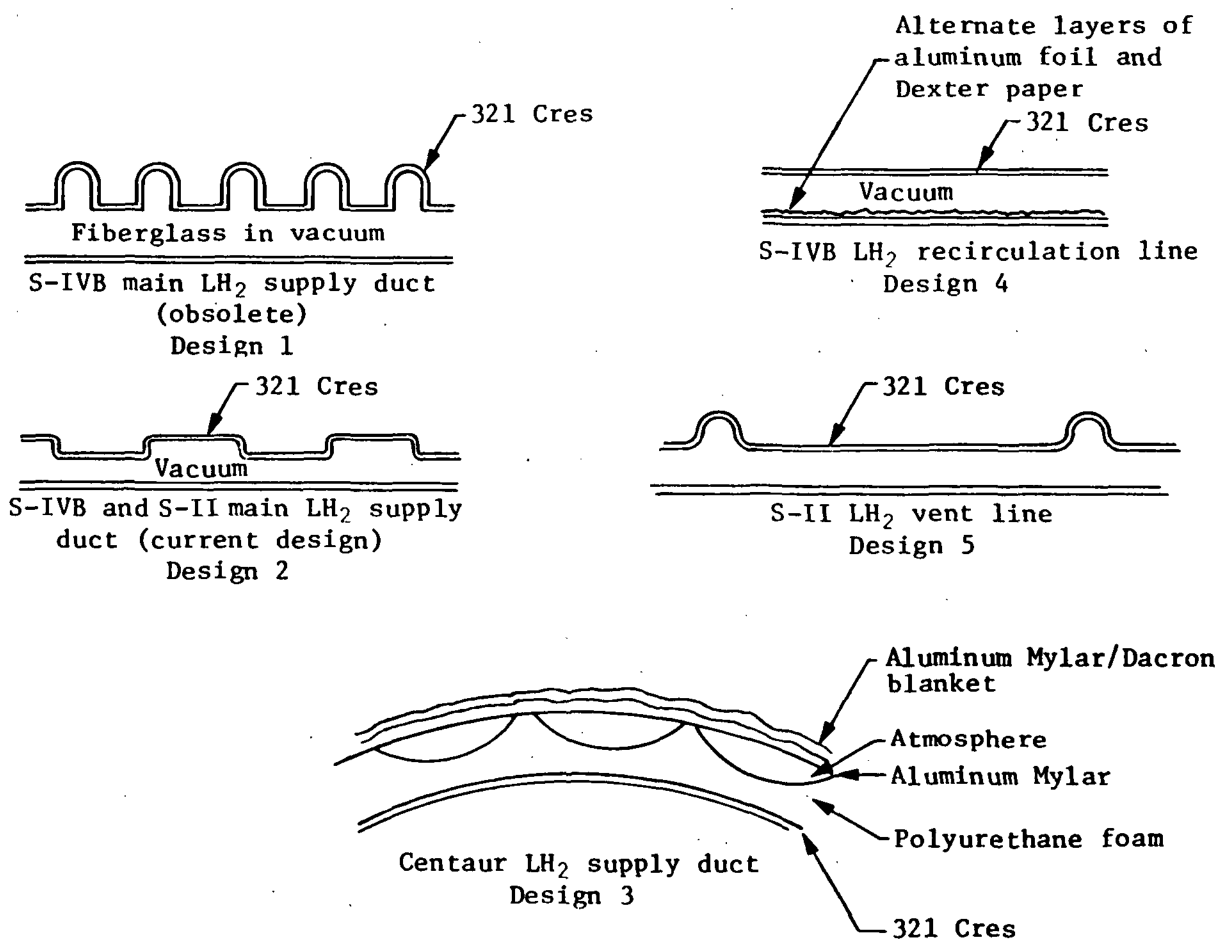
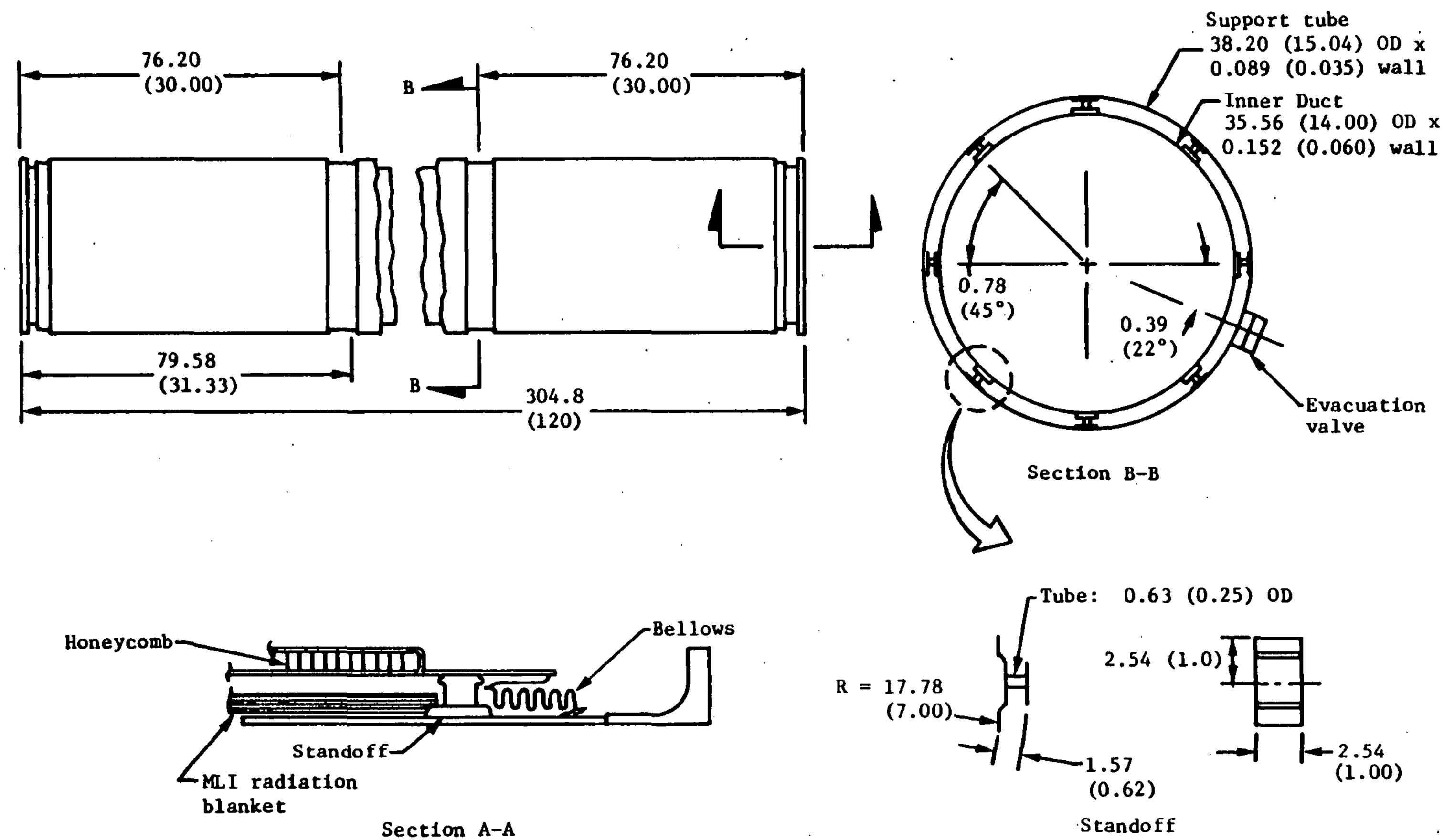


Figure 79. - S-IVB, S-II and Centaur State-of-the-Art LH_2 Lines



All dimensions in cm (in.)

Figure 80. - Advanced Design, Vacuum Jackets Line, Reference 4

RECOMMENDATIONS AND ADDITIONAL WORK REQUIRED

As a result of the knowledge and experience gained from this program, Martin Marietta Corporation makes the following recommendations for continued work in the following areas:

1) Further development of explosive bonding techniques as a method of attaching end fittings, especially using the lightweight aluminum end fittings and the efficient Inconel or stainless steel tube liners;

2) Quantification of effects on the liner of a variety of overwrap tensions and cure temperatures. Development of a useful equation to determine the required internal pressure to offset stresses caused by these tensions and temperatures;

3) Extension of the upper temperature limits for composite lines to include the Space Shuttle lox pressurization line, currently required to be operated up to 667 K (+740°F);

4) Evaluation of the low density overwrap candidates including Kelvar 49 DT-01 (formerly PRD 49), graphite, and boron. The evaluation should include analytical modeling, fabrication of tubes, and empirical verifications;

5) Comparison between the thermal performance of all-metal tubes and candidate overwrapped composite feedlines by empirical evaluation of the two using identical test settings;

6) Application and evaluation of thermal coatings for use in modifying surface emissivity of the composite. The coatings may be useful when a layer of aluminized Mylar would be exposed to damage;

7) An evaluation of the feasibility of using a braiding technique to apply the overwrap;

8) An evaluation of vapor deposited coatings on the inner composite as a means of controlling composite outgassing and improving emissivity requirements, and evaluation of vapor deposited coatings;

9) Development of the fabrication techniques to form and overwrap long radius curved tube sections;

10) Quantitative evaluation of the damage resistance characteristics of composite tube and vacuum jacketed composite tubing;

11) A program to develop nondestructive evaluation and inspection techniques for composite tubing; and

12) Additional work is required to develop analytical techniques to predict composite line external load carrying capability.

SUMMARY OF RESULTS

The purpose of this program was to evaluate fiber composites for lightweight, vacuum jacketed, cryogenic line systems for space application. The inner line (commodity line) and the outer shell (vacuum jacket) were candidates for fiber composite technology.

The concept of composite tubes includes thin walled metal liners, to provide leak-free service. The liners are overwrapped with glass-fibers to provide structural integrity and handling ability. The tubes are very lightweight when compared to conventional all-metal tubing.

Results obtained during the course of the program include the following:

1) The concept of bonding thin metal liners to composite overwrap for vacuum jacket external pressure loading was not successful. The concept of using metal liners of sufficient thickness to withstand the external pressure loading, and using the overwrap to provide structural margin and for handling protection, was successful.

2) Manufacturing techniques were developed to produce tension membrane vacuum jackets.

3) The tension membrane vacuum jacket concept used in conjunction with a composite inner line was very successful.

4) Vacuum acquisition to the 1-μ level and maintenance consisting of a 5 μ/day vacuum decay rate was shown to be attainable with vacuum jacketed composite lines. Vacuum outgassing must be accomplished through bakeout and contamination control procedures.

5) Vacuum jacketed composite lines are lightweight and could provide a significant weight saving in the Space Shuttle external tank and orbiter feedlines.

6) Vacuum jacketed composite lines are sufficiently strong and rigid so that no special handling techniques, other than ordinary care, are required.

7) Some wrinkling or slight buckling of the metallic liner during fabrication or assembly does not degrade performance of the completed composite line.

8) The test program confirms analytical predictions for the vacuum jacketed composite line performance in weight, acoustics, and external pressure loading.

9) Manufacturing methods required to fabricate the thin metal liners and apply the glass-fiber overwrap are available in the present state-of-the-art technology. Further development of explosive bonding techniques should result in further weight reduction by making possible the use of aluminum end fittings with Inconel 718 or stainless steel liners.

Technological Uncertainties. - The problems encountered during fabrication and test suggest areas of technological uncertainty where additional development is required. These are:

1) bonding;

2) standoff and end closure optimization.

Bonding: The vacuum jacket conceptual design considered the combined strength of the overwrap and the liner, assuming a structural liner-to-overwrap bond. Additional bonding development is required before this concept is workable or reliable. Composite vacuum jackets fabricated using this concept failed during evacuation. Considerable bonding evaluation was performed during failure analysis (Appendix D), which resulted in improved bonding techniques. Sufficient confidence, however, was not developed to justify continued use of bonding for structural integrity.

As a result of the bonding failure, the vacuum jacket design was changed to a metallic liner of sufficient thickness to withstand the external pressure loading. The liner is overwrapped to provide additional structural margin and damage resistance.

Standoffs and end closures: The composite standoffs and metal end closures used in the test specimens performed adequately but were not thermally or weight optimized. Further standoff and end closure development for thermal and weight optimization is recommended.

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